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REVIEW ARTICLE

Metabolomics studies on Solanaceae members under abiotic stress: A review

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Abstract

Plants are known to face various abiotic stresses, which lead to reduced yield. It has been reported that metabolite concentrations vary under different abiotic stress conditions. Metabolomic studies are widely used to analyse the compositions of various metabolites. Metabolomic studies utilise different methods such as gas chromatography (GC), liquid chromatography (LC) in combination with mass spectrometry (MS) and nuclear magnetic resonance (NMR) to analyse metabolites. The complete set of low-molecular weight metabolites present in the cell constitutes the metabolome. The amino acid proline is a major metabolite present in most stressed plants. Plant tissues exhibit altered amino acid and sugar levels under stress. As with other plant groups, similar responses are observed in members of the Solanaceae family. When solanaceous plants are subjected to stress, their cell activates the antioxidant systems to eliminate reactive oxygen species (ROS) produced in response to stress. Reactive oxygen species are scavenged by enzymatic antioxidants such as superoxide dismutase (SOD) and peroxidase (POD), as well as by non-enzymatic antioxidants, including flavonoids and ascorbic acid.

Keywords: abiotic stress; metabolomics; Solanaceae

Introduction

After Poaceae and Fabaceae, Solanaceae is the most economically important plant family. It includes a wide range of economically important vegetable crops, such as potato, tomato, eggplant and pepper. After wheat, corn and rice, the output of potatoes ranks fourth globally (1). The family comprises 90 genera, each with 3000–4000 species. The family includes perennial trees and annual herbaceous plants and occurs in a variety of terrestrial habitats, including rainforests and deserts (2). Members of the Solanaceae family are rich in carbohydrates, fats, proteins, vitamins, minerals and other essential nutrients, including flavonoids and phenols, which help protect against stress and degenerative diseases (3). The Solanaceae family typifies ethnobotany, or extensive human use of plants. It is a significant source of spices, food and medicine (4). Within the family Solanaceae, in addition to crops, several medicinal plants are used for alkaloid production, e.g., jimsonweed, deadly nightshade and black henbane (5).

Plants require specific environmental conditions for optimal growth. Various abiotic factors affect plants differently depending on their quantity or intensity. Any deviation from ideal environmental conditions, such as a surplus or shortfall in physical or chemical factors, is referred to as abiotic stress and has been shown to be detrimental to plant development, growth and production. However, the environments in which plants live are constantly changing and often adverse to their growth and flourishing. Abiotic stressors such as drought, heat, cold and salinity are examples of these unfavorable conditions. Salt, temperature and drought are the primary abiotic stressors that influence the geographic distribution of plants in nature, limit agricultural yields and jeopardize food security (6). Abiotic stress tends to erode a plant's defenses, making it more susceptible to viral and pest attacks. Abiotic stressors affect plants' growth and productivity (Fig. 1). Therefore, how they respond to these stresses is important for their ability to adapt to environmental change and survive (7). Plants react dynamically and intricately to abiotic stressors by altering their molecular, cellular and physiological makeup. Now that the genomes of numerous plant species have been sequenced, the pursuit of functional genomics has significantly accelerated the emergence of other omics, such as metabolomics (Fig. 2). Even though many metabolites remain to be identified, metabolomics has made a substantial contribution.

Over the years, attempts have been made to both improve understanding and the development of plant biology from the perspective of the small compounds produced by biological processes and to enhance plant behavior in both ordinary and stressful environments (8). The quantity and diversity of metabolites produced by plants are essential for their growth, development and adaptation to their environment. The many small-molecule metabolites that underpin crop quality and

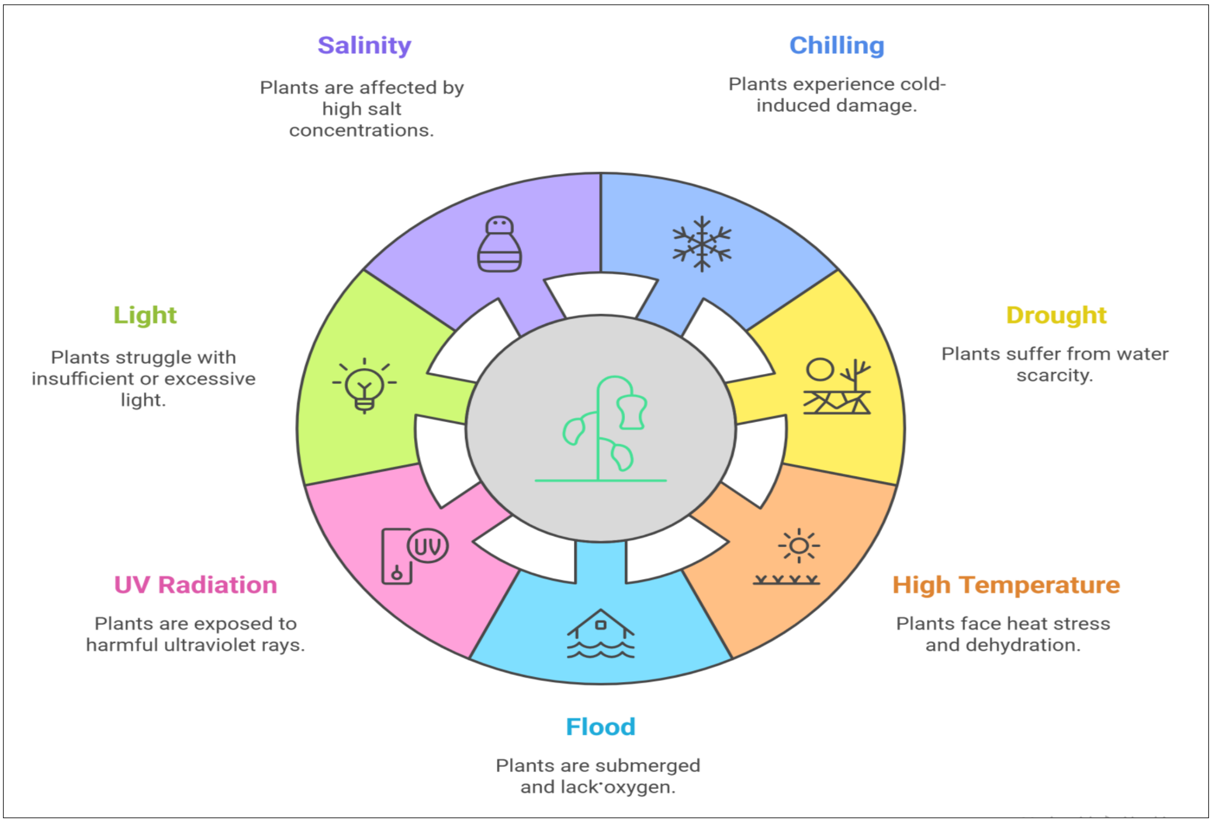

Fig. 1. Various abiotic stresses and their impact on plants.

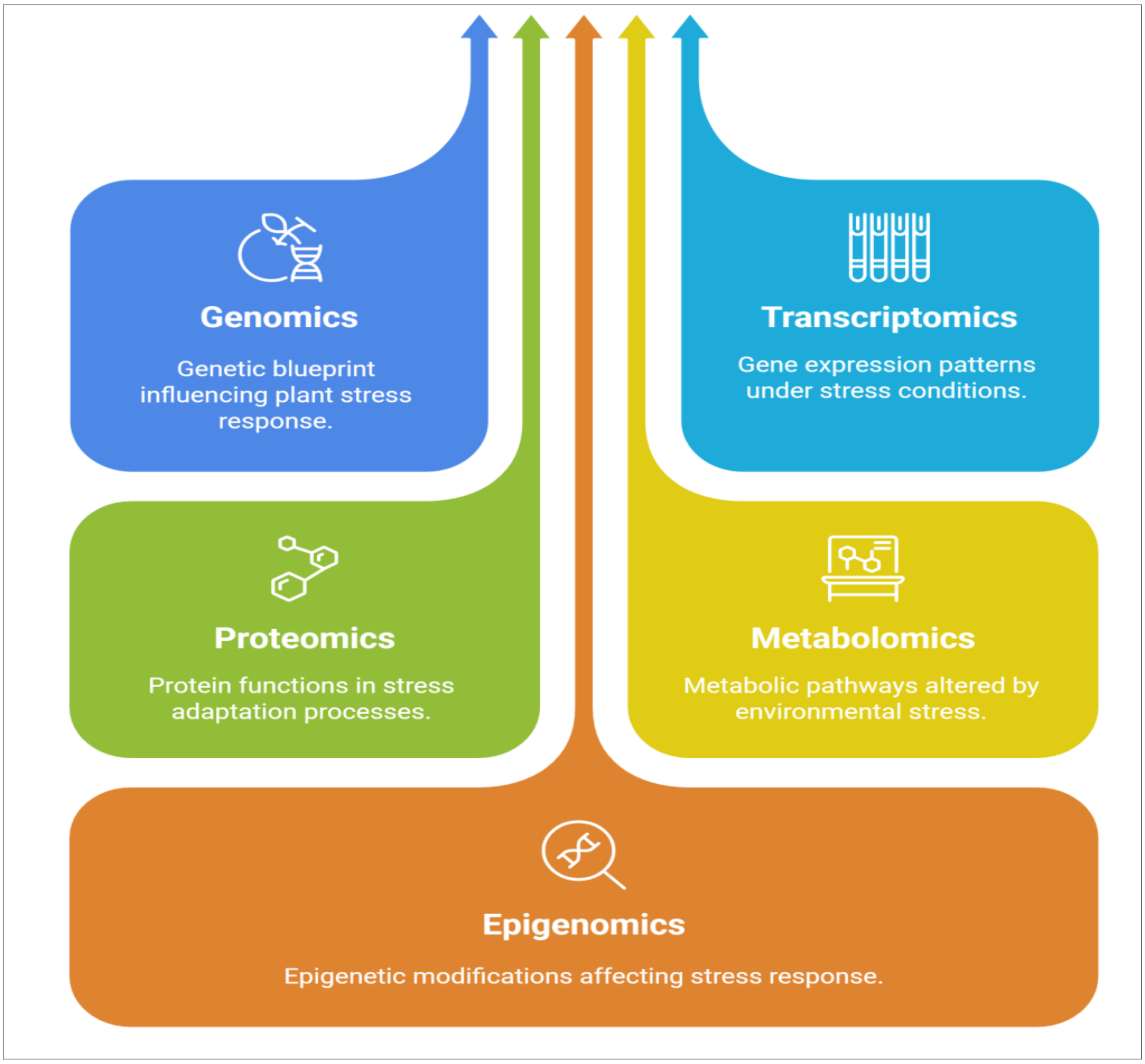

Fig. 2. The schematic illustration of various integrated “omics” approaches to analyse the plant responses to abiotic stresses.

productivity serve as significant sources of food and energy for all living organisms, including humans (9). Primary and secondary metabolites may generally be distinguished from these compounds. The latter, but not the former, are essential for a plant to survive under harsh conditions by maintaining a delicate balance with its surroundings. Also, while secondary metabolite abundances and structures vary greatly across plant kingdoms, primary metabolite abundances and architectures are highly conserved (10).

The methods and tools used in plant Metabolomics to completely identify, quantify and localise each molecule are crucial to the outcomes. Due to the intricacy of the various metabolic features and chemical abundances, it is an exceedingly difficult task. Fortunately, although it currently appears difficult to accurately and thoroughly analyse the entire metabolome of a biological sample, methods and equipment for plant metabolomics have been evolving rapidly (11). This large-scale analysis is made possible by several integrated technologies and approaches, including and mass spectrometry (MS) based techniques such as Gas chromatography mass spectrometry (GC-MS), Liquid chromatography mass spectrometry (LC-MS), Capillary electrophoresis-MS (CE-MS), Fourier transform ion cyclotron resonance–MS (FI-ICR-MS), non-destructive nuclear magnetic resonance (NMR) spectroscopy (12, 13).

The mannitol, sorbitol and dimethylsulfonium compounds, such as glycine betaine and dimethylsulfoniopropionate, sugars like sucrose and fructan, or amino acids like ectoine and proline and glycoalkaloids (GAs) like solanine chaconin, solasonine, solamargine and tomatine that act as osmolytes and osmo-protectants to shield plants from excessive drought, salt and desiccation are a few examples of plant metabolites (14). There are reports about the large-scale production of steroidal alkaloids (SAs) and their glycosylated forms (SGAs) in the members of Solanaceae under abiotic stress conditions. According to reports, SGAs in the cytosolic mevalonic acid pathway are derived from acetyl-CoA (15). Improving our understanding of the SAs biosynthesis pathway, the subcellular transport of these molecules and the regulatory and signalling factors linked to SA metabolism will probably help members of this economically significant family better understand how they tolerate abiotic stress. Additionally, this kind of study will provide tools to develop crops with altered levels of SAs through genetic engineering or traditional breeding.

Different epicuticular waxes function as mechanical barriers to pathogens and protect plants from excessive water loss during drought. The degree of saturation of membrane fatty acids can significantly affect cold tolerance. Numerous small molecules protect plants from oxidative damage caused by various stressors. Glutathione (GSH), anthocyanins, ascorbic acid, tocopherols and carotenoids, which remove active oxygen intermediates, protect plant tissues from oxidative stress. The general phenylpropanoid pathway is activated during plant defense responses and phytoalexin production and lignin biosynthesis are also induced. Small molecules produced in response to stress, such as jasmonic acid (JA), methyl jasmonate, salicylic acid (SA) and methyl salicylate, can also serve as chemical messengers that trigger systemic defense and acclimation responses (16). In this review, we summarize our current understanding of the metabolome under abiotic stresses, including drought, waterlogging, salinity and high and low temperatures, in the Solanaceae family. The metabolomic investigations and methods used to elucidate the mechanisms of abiotic stress tolerance in members of the Solanaceae family are summarised in Table 1.

A brief account of common techniques used in metabolomics studies

Gas chromatography mass spectrometry

Gas chromatography mass spectrometry (GC-MS) is the most established metabolomics technology. In it, a chromatographic method is used to separate the complex mixture and a mass spectrometer (MS) also provides chemical and structural information (15).

Volatile and thermostable compounds can be separated only by gas chromatography and other polar metabolites must be derivatised to become volatile (16). Based on thermodynamic properties, components get separated in GC. A mass analyser follows GC. Before entering the mass analyser, components are converted into charged particles by using various methods, such as electron impact and electrospray ionisation. Determining the mass-to-charge ratio of ions is the fundamental goal of MS. The mass analyser separates charged ions based on their mass-to-charge ratio. All types of mass analysers, including ion traps, single quadrupoles, time-of-flight (TOF) and magnetic mass spectrometers, operate on different principles. The time-of-flight analyser offers high scanning speed, has higher ion-collection efficiency and achieves a resolution of up to 40000 (15). The mass analyser then generates 3D information on the target compound. Gas chromatography is widely used for metabolite profiling. Databases such as the National Institute of Standards and Technology are used for the annotation of GC-MS peaks (17).

The literature reports a study in which GC-MS-based analysis of methanolic or ethanolic extracts of salt-stress-induced callus tissue of *Solanum melongena* L. showed the presence of secondary metabolites such as alkaloids, saponins, steroids, tannins/phenolics, flavonoids, glycosides and reducing sugars (44). Another study reports the variation of endogenous hormone profile of the Solanaceous plants under salinity stress. In this GC-MS-based metabolomics study, it is revealed that crosstalk between endogenous hormones plays an important role in abiotic stress response (45).

Studies on metabolites associated with chilling tolerance of tomato fruit pericarp (*Solanum lycopersicum* L. cv. Micro-Tom) using GC-MS metabolite profiling reports 363 analytes from fruit pericarp of which 65 are reported to be metabolites (46). Increased production of volatile terpenoids was reported in tomato by researchers using SPME-GC-MS studies (47). Gas chromatography mass spectrometry is cheaper as compared to the other techniques, but it is limited to thermo-stable and volatile compounds.

The use of GC-MS in metabolomics investigations of members of the Solanaceae has been documented extensively. Table 1 compiles the reports on common techniques used for the metabolomics studies of Solanaceae members under abiotic stress.

Liquid chromatography mass spectrometry

The mobile phase in liquid chromatography mass spectrometry (LC-MS) is liquid that is passed through the column containing the stationary phase which resists the flow of the liquid. High pressure is required to make the mobile phase rapidly flow in the column. It does not involve any derivatisation process, i.e. there is no

Table 1. The metabolomic studies and techniques applied to identify the mechanisms of abiotic stress tolerance in the Solanaceae family members

Sl. No	Plants studied	Techniques used for the study	Type of Stress	Major metabolites analyzed	Key findings	Citations
1.	Potato (*S.tuberosum* and *S.acuale*)	GC-MS	Freezing tolerance	metabolites except ABA and SA	Types of aminoacids, sugars and other metabolites were reported to be different in chilling stress-treated samples. SA and ABA signalling pathways were activated in response to chilling stress treatment. *S. acaule* reported to be more freezing tolerant than *S. tubersosum.*	(17)
2.	Habanero (*Capsicum chinense*)	LC-MS	Salinity, nitrogen and phosphorus deficiency	Edaphic stress	The work was for untargeted metabolomics, measuring changes in the Habanero fruit pericarp under increased salinity and nitrogen and phosphorus deficiency at three ripening stages. The result shows a metabolite substitution under nitrogen deficiency in the pericarp. Phosphorus deficiency showed an overall decrease in metabolite diversity and a negative impact on postharvest shelf life.	(18)
3.	Bell pepper	GC/Spectrophotometry	multiple stress interactions (SA and H_2O_2)	Phenolic compounds, low molecular weight metabolites campesterol, stigmasterol, (-tocopherol, succinic acid, asparagine and ascorbic acid. In addition to glyceric, fumaric, maleic acid and isoleucine	The study was conducted to analyze the effect of multiple stress interactions, elicitor concentrations and electrical conductivity on the concentration of secondary metabolites to relate their response to metabolic pathways. Shows significant change in aminoacyl t-RNA and valine-leucine-isoleucine biosynthesis and alanine-aspartate-glutamate metabolism, glycoxylate-dicarboxylate cycle, arginine-proline and citrate.	(19)
4.	*Withania*	LC-MS	Salinity	glycyl-hydroxyproline (8*X*),tyrosyl-valine (2*X*), 3-hydroxy-beta-ionone	The investigation was on the effect of NaCl on growth, photosynthesis, biochemical traits, tissue-specific withanolide and untargeted metabolites in *W. somnifera.* NaCl stress significantly enhanced withaferin A, withanolide A and withanone. LC-MS-based untargeted metabolite profiling revealed 37 differentially accumulated metabolites, including glycyl-hydroxyproline (8X), followed by tyrosyl-valine and 3-hydroxy-beta-ionone.	(20)
5.	Potato	UHPLC-HRMS/MS; LC-MS and NMR; Q-Exactive high-resolution tandem mass spectrometer equipped with heated ESI	post-harvest stresses such as wounding and light exposure	Steroidal glycoalkaloids (SGA)	Two-year research conducted on Magnum Bonum and five other table potato cultivars has been reported for their SGA content under light exposure. The result of the study shows that Magnum Bonum has a high SGA response to light exposure and the variety Bintje has a decrease in SGA content under the same treatment. The study results also reveal the separate metabolic regulation pathways of SGA and calystegine levels in situations of increased accumulation of SGA.	(21)
6.	*Capsicum annuam* L	LC/MS/MS	Cold stress	Polyamene, hormone, osmolyte, putrescine, spermine, spermidine, ABA, JA, raffinoseand proline	Two Capsicum cultivars (cold –sensitive, XS and cold-resistant GZ) were analysed in this study to analyse the response to cold stress. Metabolomic profiling shows that the content of metabolites like PAS, plant hormones, osmolytes, putrescine, spermine, spermidine, ABA, JA, raffinose and proline is increased under cold stress. The study also reveals that there is a deviation in MAPK signalling and (ROS signalling pathways in response to cold stress in *Capsicum*.	(22)

7.	Pepper	LC-HRMS; UHPLC-MS	Cadmium (Cd) stress	Amino acids; fatty acid pathway; Volatile oil Compounds	The study reports the impact of Cd-contaminated soil stress and nano-Selenium on the metabolism, fruit nutritional quality and volatile organic compound content in chilli pepper plants. Study includes the analysis of differential metabolites in roots and fruits, including amino acid metabolic pathways and capsaicin production pathways. Results show that the amino acid content (Pro, Trp, Argand Gln) in roots and fruits (Phe, Glu, Pro, Arg, Trp and Gln) is increased drastically by metalic stress. Volatile organic compounds like amyl alcohol, linalool oxide, E-2-heptadehyde, 2-hexenal, ethyl crotonate and 2-butanone, capsaicin, norhydydrocapsaicin and dihydrocapsaicin levels also were seen to increase under metallic stress.	(23)
8.	Potato	^{1}H-NMR; LC-MS	Polluted water [Fly Ash (FA) treated Acid mine drainage (AMD)]	secondary metabolites	Reports of the study revealed the usage of analytical platforms like 1HNMR and LC-MS to identify the metabolites in potato plants which are treated with different concentrations of FA and AMD. The results of the analysis revealed the change in both primary and secondary metabolites. A significant increase in the production of secondary metabolites was noted in plants irrigated with 75 % FA: AMD concentration in the mixture .	(24)
9.	Capsicum	UPLC-QToF MS	Cold and salinity	flavonoids	In this study two *Capsicum* species were exposed to chilling, salinity stress and its combination to investigate the impact of these stresses on metabolome content in leaves. Study results show that chilling stress increases secondary metabolism and salinity stress decreases cell wall modification and solute transport. Metabolome profiling shows enhanced production of flavonoids like apigenin, rutin, kaempferol, luteolin and quercetin in Capsicum biomass residues in response to chilling or salinity stress or their combination.	(25)
10.	*Capsicum annuam* L.	UHPLC-QE orbitrap/MS analysis; LC-MS/MS analyses	Cold stress	Polyamenes, phytohormones, osmolytes		(22)
11.	*Capsicum annuum* L	HPLC-MS/MS	Storage	Phenylalanine, glycyl-tyrosine	In this study, pepper lines with different levels of storage resistance, A 144 and A 361, are used for physiological examination, transcriptomics and metabolomics on different days of post-harvest. The study shows the genes responsible for ethylene–responsive transcriptional factor (ERFs), polygalacturonase (PG), cellulose synthase (CESA), abscisic acid insensitive (ABI) < protein kinase 2(SnRK2) and protein phosphatase 2C(PP2C) and metabolites such as phenylalanine and glycyltyrosine are expressed differently in various storage times. The study shows the variation in flavonoid biosynthesis, GSH metabolism and cysteine and methionine metabolism pathways.	(26)
12.	*Solanum tuberosum* L	LC-MS; UHPLC	Heat stress	Phenolics, Amino acids, Fatty acids, Steroids, Tyrosine, GSH, Isoquinoline alkaloids	The study reports about the transcriptomics and metabolomics analysis of potato tissue samples under heat stress. Study results the variation (both upregulation and downregulation) of genes and variation in the production of compounds (both positive and negative) in leaf tissues in response to heat stress. Both metabolite and transcript enrichment for flavones and flavonol under prolonged heat stress were also noticed in this study, Study generates a novel set of metabolome and transcriptome profiles of potato under heat stress.	(27)

13.	Tomato	LC-FTICR-MS and MS/MS	Nitrogen deficiency, Chilling temperatures, Elevated light intensities	Secondary metabolites	This report is about a comparative analysis of the response of wild and cultivated varieties of tomatoes under diverse stress conditions, such as nitrogen deficiency, chilling or warm temperature, high light intensity and a combination of all. Observations of these experiments show that Nitrogen deficiency made a serious impact on the plants and induced secondary metabolism in both species. Cultivated variety had enhanced production of mono caffeoylquinic acids in response to nitrogen deficiency.	(28)
14.	Tomato, eggplant and pepper	LC-MS	Comparative analysis of fruit metabolomics	Fruit Polyphenolics	The work reports about a comparative study on fruit metabolomics to elucidate the metabolic regulation of fruit polyphenolics in major Solanaceous crops viz, tomato, eggplant and pepper. Comparison among various cultivars of pepper (*Capsicum annuum* cv.) cultivars also were conducted. LC-MS based metabolomic analysis showed metabolic shift between hydroxycinnamates and flavonoids in *Capsicum* and anthocyanin in *Capsicum* cultivars.	(29)
15.	Tobacco	UHPLC-Q-TOF/MS	Effect of coronatine in polyethylene glycol (PEG) stress	Sugar, Sugar derivatives, organic acids, nitrogen-containing compounds	The effect of cornatine in tobacco under polyethylene glycol (PEG) stress was analysed. It is noticed that the cornatine treatment ameliorates the polyethylene glycol (PEG) stress. Under osmotic condition enhanced metabolomic changes were noticed in tobacco leaves. The study shows that the essential metabolites, such as sugars, sugar derivatives, organic acids and nitrogen-containing compounds, play a crucial role in osmotic stress management in tobacco plants.	(30)
16.	*Capsicum annuam* L.	database MWDB; Partial least squares-discriminant analysis (PLS-DA)	Heat Stress	Sugars, Proline, Total protein,	In this study a comparative analysis were conducted between heat sensitive and heat-tolerant cultivars (17CL30 and 05S180) Study showed accumulation of a huge number of diverse metabolites in both sensitive and tolerant cultivars under study The results reveal that the GSH metabolic pathway plays a crucial role in Capsicum in response to heat shock.	(31)
17.	Potato	GC-MS	Stress to phosphate-based fungicide	Sugar and alcohol	The impact of phosphate-based fungicide on potato tubers was studied by the application of the fungicide through foliar and post–harvest application. GC-MS based studies showed that metabolites like sugars, amino acids or alcohols are accumulating in response to stress.	(32)
18.	*Withania*	GC/MS	Drought stress	Isoprenoids, phenols and alkaloids	Water stress had induced in *Withania somnifera* and the drought stress tolerance related metabolic data were observed in this study. It is noticed that the biosynthesis of minor compounds like isoprenoids, phenols and alkaloids is increased under water stress. Pathways leading to glucose, fructose, fructan productionand interconversion of triose phosphates to hexoses and hexose phosphorylation were noticed to be increased under water stress.	(33)

19.	African Egg plant	GC-MS/MS	Drought stress	Amino acids, sugars and organic acids	GC-MS studies were reported in 19 accessions of African eggplants under drought stress during different growth stages. Proline, glutamate, sucrose, fructose and tricarboxylic acid cycle metabolites were shown to accumulate in response to stress.	(34)
20.	Tomato	LC-QTOF-MS	Heat Stress	Alkaloids, Polyamenes, Flavonoids	LC-MS-based studies of pollen metabolite of tomato plants were conducted during various developmental stages and under various range of heat stress It is observed that the heat stress causes accumulation of flavones in pollen grains Young pollen grains showed an increased amount of PAS and alkaloids, while in mature pollens, flavonoid content was higher.	(35)
21.	*Nicotiana benthamiana*	GC-MS	Water stress	Sugars, Sugar alcohols, Amino acids	GC-MS studies were conducted in *N. benthamiana* plants to analyse metabolomic responses under fungal infection. From the leaves of infected plants, sugars, Amino acids, fatty acids and sugar alcohols were detected. Fungal-infected plants under water-deficient conditions show enhanced production of metabolites like cytosine, diethylene glycol, galactinol, glycerol, heptadecanoate, mannose, oleic acid, proline, rhamnose, succinate and urea. Fungal colonisation also showed an increase in root dry mass and relative water content under drought stress. All over the research results indicate that the fungal colonization enables the plant to defend against water stress more effectively.	(36)
22.	Tomato	LC/MS; LC/MS2; GC/MS	Drought stress	Amino acids, Carbohydrates, Cofactors, Prosthetic groups, Secondary metabolites and Xenobiotics	Deviations in metabolites, physiology, m RNA levels and promoter dynamics under drought stress in tobacco plants were analysed in this study Both general (the responses common in most plants) Species or family-specific responses to drought stress stimulations were observed in this research. Tobacco/Solanaceae specific metabolite 4-hydroxy -2 –oxoglutaric acid (KHG) content in roots shows abundance under water deficit stress. In this study serine and glycine content reported to be decreased in leaves and roots under drought stress. Higher rate of accumulation of compatible solutes (sugars, alcohols, oligosaccharides, oxidative products of ROS amelioration).	(37)
23.	*Nicotiana langsdorffii*	HPLC coupled to High resolution mass spectrometry (HRMS)	High Temperature, Water deficit, high chromium (Cr) concentrations,	Lipids, acylsugards and glykoalkaloids, PAS	The response of the wild and transgenic Nicotiana species to diverse abiotic stresses, viz. high temperature, water deficit and high Cr concentrations, was analyzed. Impact of introduced genes under abiotic stresses were studied using HPLC coupled to HRMS. It was noticed that heat stress induced a set of special metabolites. Enhanced production of acylsugars and glykoalkaloids also were reported. Combination of drought and Cr Stress showed increased antioxidant levels and repaired lipids.	(38)

24.	Tomato	LC–MS and GC–MS	Nitrogen, Phosphorus and Potassium-deficient	soluble sugars; amino acids; soluble sugars and amino acids	Difference in content of metabolite components like amino acids, organic acids and soluble sugars in xylem sap of Tomato plants under macro nutrients (N, P, K) deficient conditions were studied using liquid chromatography in this research. The nutrient deficiency is reported to increase the metabolite concentration in xylem sap. Increased concentration of γ-aminobutyric acid (GABA) and glutamine was reported in the xylem sap content under nutrient scarcity, in addition to organic acids and soluble sugars.	(39)
25.	Tomato	GC-MS/MS	low oxygen stress	Glycolysis and TCA cycle products	The study aimed to analyse the metabolic responses of plant organs to low oxygen, in cultured tomato cells. The study shows the increased intermediates of glycolysis in addition to increases in lactate and sugar alcohol content under low oxygen stress. Enhanced fermentative metabolism and sugar alcohol synthesis while hindering the TCA cycle also were noted in the studied samples.	(40)
26.	Tobacco	HPLC-MS/MS	Water stress	Phenolic compounds	Variation in phenypropanoid profile in *Nicotiana tabacum* L.c. Two different conditions, i.e., senescent and non-senescent parts of the plantand watered or young plants with water deficit, were analysed. It is reported that there is an increase in concentration of polyphenol compounds under water deficit or senescence. But the concentration of 3-Hydroxycinnamic acid amides (HCAA) was less in senescent samples. 5-O-caffeoylquinic acid (neochlorogenic acid) was reported in all the samples. This study reported the presence of kaempferol-7-O-neohesperidoside for the first time from *Nicotiana tabacum* samples.	(41)
27.	Tomato cultivars	HPLC/UV-PAD/ESI-MSn	Water stress	Phenolic metabolite	Drought tolerance capacity of five different cherry tomatoes was studied in this research. Decrease in shikimate pathways and phenolic compounds under water stress were reported in this study. The cultivar Zarina showed more tolerance to water stress with enhanced activities of flavonoid and phenylpropanoid production and reduction in degradation-related enzymes.	(42)
28.	Tomato	GC-MS	Water stress	TCA products	Fruit samples from the irrigated and non-irrigated tomato plants (cultivars and hybrid varieties) were analyzed using GC-MS-based metabolite profiling. Significant deviation in amino acid concentrations was shown in both varieties and cultivars under study. Increase in concentration of fattyacids and organic acids were reported in hybrid variety under water stress. Variations in sugars, sugar phosphates, sugar alcohols and many other metabolites were observed in both the genotypes under investigation. Increase in aminoacid contents, alanine, aspartate, GABA, glutamate, glycine, homoserine, isoleucine, proline, serine and valine were reported, but a decline in cysteine, glutamine and glycine was also observed in this study.	(43)

chemical modification of the molecules and the sample is prepared in liquid form. With advances in technique, different types of columns are available which include stationary phase with different size and chemical properties. The selection of columns comprised of ion exchange, reverse phase, hydrophobic interaction column (16). For high resolution and sensitivity, Ultra-Performance liquid chromatography (UP-LC) is used (48). An atmospheric pressure ionisation (API) interface is used to connect LC with MS. The API technique comprises atmospheric pressure chemical ionisation and electrospray ionisation (16). These techniques are soft ionisation techniques and do not break the macromolecule. There are many MS instruments, including magnetic analysers, quadrupole and TOF spectrometers. Two MS can be used in combination such as Q-TOF mass analyser (16). Various built-in software tools are available for LC-MS analysis. Liquid chromatography mass spectrometry is a better technique than GC-MS for the analysis of thermostable compounds. A common problem in LC-MS includes the pressure shock, which affects column efficiency. Table 1 lists metabolomic research and methods for identifying abiotic stress tolerance mechanisms in members of the Solanaceae through a variety of liquid chromatographic techniques.

An LC-MS-based metabolome database (MoToDB) for tomato is available for covering metabolomics of its fruits (49). High-performance liquid chromatography analysis of samples from the vegetative parts of salinity-stress-induced *Solanum incanum* plants shows variation in glycoalkaloid content, including Solamargine and Solasonine (50). Researchers reported the LC-MS -based quantification of SGAs from *Solanum xanthocarpum* (51). Another study reports the use of reversed-phase high-performance liquid chromatography coupled with diode-array detection to detect steroidal glycosides across different *Solanum* species (52). Liquid Chromatography Mass Spectrometry-based identification of phytochemicals, viz. Solasonine, Solamargine and other triterpenoids from *Solanum nigrum* L. are reported by scientists (53). High Performance Liquid Chromatography and LC-MS studies have been reported on sodium chloride (NaCl) induced salinity stress and its impact on secondary metabolite content in *Solanum villosum* Mill. The results of the study show a considerable increase in leaf contents of Caffeic acid, Lutein and beta-carotene in *S. villosum* under NaCl stress (54). High performance liquid chromatographic studies show that exogenous application of Abscisic acid (ABA) increases the synthesis of phenolic compounds in *Physalis angulata* L. (55). A comprehensive glycoalkaloid profiling from the vegetative parts of underutilised Solanaceae plants was reported using HPLC-TOF-MS. The study presents a profile of 51 GAs at varying concentrations across different species (56).

Reports on phytochemical studies of genetically modified and wild varieties of *Nicotiana* species (*N. glauca* and *N. langdorffii*) using High-performance liquid chromatography-tandem mass spectrometry (HPLC–MS/MS) and GC-MS provide a better understanding of phytohormones (57). Ultra-high-performance liquid chromatography–mass spectrometry (UHPLC/MS) was reported to be used effectively for profiling acyl sugar diversity in various species of Solanum (S. lycopersicum and S. habrochaites).

Nuclear magnetic resonance spectroscopy

Nuclear Magnetic Resonance (NMR) spectroscopy is a physical process in which atoms with non-zero magnetic moment get flipped under the influence of a magnetic field and electromagnetic radiation (16). Atoms with nonzero spin and nonzero net magnetic moment are ^{1}H, ^{13}C and ^{31}P. In the case of ^{1}H NMR, the H atom aligns with the direction of the applied magnetic field and is flipped when electromagnetic radiation of a specific frequency is applied; this flipping is known as resonance. When this flipping occurs, the signal is generated. The neighboring environment and the electron cloud around the H atom shield or de-shield the atom, thereby affecting the signal position and chemical shift. Neighboring H atoms also influence one another, causing signal splitting. When analysing a mixture, 2D NMR is advisable. 2D NMR includes Correlation spectroscopy (COSY), Heteronuclear single quantum coherence (HSQC) and Heteronuclear multiple bond coherence (HMBC) (58). Nuclear magnetic resonance is less sensitive than MS but remains a powerful tool for identifying and quantifying metabolites in plants (59). Because NMR is nondestructive, spectra from cell suspensions, tissues and even entire plants can be recorded (48). ^{31}P is used to profile phosphate esters and ^{13}C is used to profile amino acids, lipids etc (60). Reports are available on the successful application of NMR techniques for metabolome profiling of members of the Solanaceae under abiotic stress (61–63).

Effect of drought stress on the metabolome of Solanaceae family

Drought stress causes significant morphological and physiological changes in plants, as well as other responses. Plants respond differently to water stress depending on the phenological stage at which it occurs, its duration and its severity (64). However, persistent high-intensity drought stress may impede plant growth, alter morphological traits and biomass distribution patterns, or even cause plant mortality (65). On a global scale, drought is undoubtedly the most challenging and harmful abiotic stress. According to one definition, a plant's ability to continue growing productively despite low leaf water status is its relative drought tolerance. Due to solute concentration gradients and osmosis, drought reduces the cell's water potential and causes it to lose turgidity. Some plants can modify their osmotic potential to endure dehydration or maintain turgor pressure by actively accumulating solutes known as osmo-protectants or compatible solutes. Plants have developed a variety of defense avoidance and tolerance methods to deal with drought stress (66). Additionally, plants under drought stress assemble more reactive oxygen species (ROS), such as hydrogen peroxide (H_2O_2) and the superoxide anion (O2•) (67). Secondary metabolites in plants are crucial to how they respond to stress (68). Drought exposure results in a sharp drop in physiological and plant growth indicators. Through antioxidant defense mechanisms, plants can tolerate damage caused by oxidative stress (69, 70). Furthermore, under stress, plants can maintain osmotic balance and quickly repair oxidative damage due to the accumulation of osmolytes such as proline and carbohydrates (71, 72). Another common response of plants to stress is changes in the expression levels of phytohormones (73). There were reductions in the potato plant's shoot and root length, shoot and root dry weight and leaf area. It was shown that drought stress decreased total chlorophyll a and b concentrations in potato. Stress from the drought decreased the expression of the examined hormones, including indole acetic acid, Indole-3-butyric acid, GA1 and GA4, in potato plant tissue (74). In tomato, leaf stomatal conductance is strongly impacted by drought stress. In drought-stressed plants, the photosynthetic efficiency was also reduced (75). Strigolactones aid shoots in adapting to drought, as strigolactone-depleted plants are susceptible to drought due to stomatal hyposensitivity to ABA. In contrast, roots' reduced synthesis of strigolactones during drought suggests that their digestion and function are organ-specific. Since strigolactones may be transmitted acropetally, such a decline may also affect shoots as a sign of systemic stress throughout the body (76). Dryness downregulates cyclin-dependent kinase activity, reducing the number of meristematic cells and slowing cellular division and extension, which results in fewer leaves and less leaf area (77–80). Under drought stress, the plant produces fewer fruits overall and fewer fruits per unit area and under water stress, it produces fewer fruits overall. There are reports about lower concentrations of micronutrients, viz. N, K, zinc (Zn) and manganese (Mn), in plants cultivated in water-restricted environments, except for P (64). Fruits with a bitter taste may result from dry conditions and extreme heat (81). Long-term drought stress reduces bloom production and causes early blossom fading.

A greenhouse experimental study on the interaction of drought-stressed potato plants with entomopathogenic nematodes (EPNs) reports that the drought stress weakens the tritrophic interaction (82). Detailed investigation of the effect of water deficit on the growth and development of various Solanaceae was reported by various researchers (83). A study on phenotypic and physiological variations in tomato leaves under dehydration treatment reported that severe damage occurred after 24 hr of treatment and, as with drought stress, dehydration increased ROS accumulation. Transcriptomic analysis of the treated samples shows a significant number of DEGs including Transcription Factors (TFs) of various families and drought-responsive genes. The study verified the expression pattern of various TFs (84).

In a study, the variations in metabolomic pathways in tomato seedlings in response to developmental and environmental cues were analysed. The study reveals the interplay between depletion of stored molecules and de novo synthesis. Results of this study give information on metabolic networks regulating flavonoid biosynthesis in tomato (85). Based on the report of a comparative metabolomics study of two hybrid varieties of tomato, the hybrid HTT VRNTH18283 performs better than HTS VRNTH19072 against the detrimental effects of high temperature due to its changed physicochemical profile, enhanced metabolite compositional diversity and discriminatory metabolite biomarkers.

Plants under drought stress produce compounds such as amino acids, which increase the concentration of soluble solids in fruits (86). During drought stress, mannitol, ononitol, myo-inositol, fructans, trehalose, proline, glycine betaine and polyamines (PAS) accumulate to considerable levels. It is reported that the production of tropane alkaloids, GAs and nicotine is enhanced by exposure to abiotic conditions. There is evidence that alkaloids such as atropine and scopolamine influence physiological responses to abiotic stress. In *Datura* high salinity is reported to be cause, high salinity has been reported to cause the accumulation of atropine. Similarly, nicotine content is also noted to be increased because of the influence of various environmental cues. Abiotic stress conditions like light exposure, mechanical injury and improper storage conditions have been shown to enhance the accretion of SGAs, Solanine and Tomatine in potatoes and tomatoes, respectively.

Additionally, certain proteins, including those encoded by genes for late embryogenesis abundant proteins and stress-sensitive transcription factor genes, are stored in plant cells as a stress-defense strategy (87). The roots and stems' weight while under drought stress decreased both wet and dry. It also decreased the relative water content (88). One of the plants' biological functions most susceptible to dryness is canopy development, which is driven by the irreversible elongation of individual plant cells (89). It harms essential molecules, including proteins, lipids and DNA (90). Drought stress further impairs product quality, such as by elevating common scab incidence, while disrupting multiple metabolic pathways that govern physiological and developmental processes (91, 92). Reduced ribulose bisphosphate synthesis, reduced Rubisco activity and reduced carboxylation efficiency are examples of biochemical alterations. Under stress, the steady loss of maximal metabolic capacity saturates the photosynthetic rate, suggesting that ribulose bisphosphate carboxylase/oxygenase and other enzymes of the photosynthetic emission reduction cycle are implicated. Restriction of ATP production likely limits ribulose bisphosphate synthesis, driven by the coupling factor's gradual loss or inactivation due to rising ionic magnesium (Mg^{2+}) concentrations. Photosynthesis under stress may be partially improved by selectively increasing the activity of Rubisco activase, a nuclear-encoded chloroplast protein, although such improvement is typically minimal (93). Reduced CO_2 assimilation results in less $NADP^+$ regeneration at the level of electron transport. Distinct signaling pathways activate appropriate transcription factors and initiate phosphorylation cascades that, in turn, mediate cellular responses to drought in potato. As the potato plant's main defense mechanism against stress, these transcription factors control gene expression. Complementary solutes help stabilise enzymes, preventing denaturation caused by drought stress. Potato plants' sophisticated adaptive modifications in response to limited water supply are frequently accompanied by negative pleiotropic impacts. As water stress increases, non-stomatal leaf components known as "mesophyll" significantly reduce transpiration (94). These effects lead to a global decrease in production.

Effect of waterlogging on the metabolome of the Solanaceae family

Water logging stress is one of the main abiotic restrictions on growth, development, species dispersal and agricultural output. In plants stress is caused by deeper submersion and waterlogging of the soil. This stress is brought on by decreased oxygen availability for plant cells as a result of flooding or compacted soil. Floodwater blocks airflow by filling soil pores and because dissolved oxygen diffuses slowly in stagnant water, only a thin surface layer of soil contains oxygen. Crop losses from prolonged floods can reach > 10 % and in extreme circumstances > 40 %. The physiological functioning is disrupted, adversely affecting vegetative and reproductive growth. Stomatal closure, which impacts both gas exchange and passive water absorption while also severely affecting anaerobic conditions in the rhizosphere, is the earliest sign of flooding damage. Reduced transpiration causes early senescence and leaf withering, which ultimately leads to foliar abscission (95). Impaired morphological (reduced leaf area, early abscission) and physiological (lower photosynthetic efficiency in younger leaves, photoinhibition, affected PS II functionality) characters were reported in flooded plants of eggplants (96). A comparative study conducted to assess the response of water stress (drought and flooding) in various genotypes of brinjal (*Solanum melongena* L.) and *Solanum microcarpon* L. reports the greater sensitivity of stomata under flooding than to drought in various *S. melongena* genotypes. The study also reports that some genotypes exhibit better photosynthetic performance under drought than under flooding. Variation in the speed of the stomatal mechanism also was reported from this study in response to extremes of water level (97). Various studies are available with reports on variation in morphological, biochemical and physiological parameters of solanaceous members under waterlogged conditions (98–103).

Root respiration shifts from aerobic to anaerobic conditions under flooded conditions, which are either inadequately (hypoxia) or completely (anoxia) non-aerated, in which gas transport is highly restricted. This is highly detrimental to plant growth. The availability of nutrients to plants is significantly reduced in soils with low O_2 partial pressures. Anaerobic bacteria predominate when oxygen availability in the soil is limited, resulting in severely reduced conditions in the rhizosphere, where toxic concentrations of iron and manganese ions, hydrogen sulfide, sulfides, butyric acid and lactic acid accumulate (104). In the case of tomatoes, waterlogging increased *in vivo* H_2O_2 levels, lipid peroxidation and relative ion leakage while decreasing chlorophyll content (105). In tomato, Na concentrations rose during waterlogging, whereas K concentrations fell. Decrease in the Ca level reported in roots of tomato as well as fat, protein and total solids dissolved all decreased, while fruit moisture, Phosphorus (P) and Sodium (Na) increased (106). In *Capsicum annuum* L., ROS are controlled, antioxidant activity increases, lignin is produced and stress-tolerance genes are expressed. Furthermore, waterlogging causes the accumulation of hazardous chemicals, including ethanol and ethanol produced by anaerobic respiration. Moreover, waterlogging increased alcohol dehydrogenase (ADH) activity, activated ABA sensors, activated ABA-dependent transcription and reduced ABA levels in pepper. Waterlogging can make it more difficult to synthesize ethylene. The direct precursor of ethylene, 1-aminocyclopropane-1-carboxylic acid, is produced in the anaerobic root and transported to the shoot, where it is promptly converted to ethylene, as previously reported (107). Waterlogging reduced leaf area and nitrogen use efficiency in tamarillo plants. Waterlogging episodes improved dry matter partitioning to stems (by about 30–35 %) (102). Eggplants are particularly susceptible to waterlogging during the blooming and fruiting stages (108). When it comes to tobacco, the amount of malondialdehyde (MDA) grew dramatically as waterlogging progressed, while the levels of chlorophylls and soluble protein declined. Superoxide dismutase (SOD), peroxidase and catalase (CAT) activities also differed in this direction, increasing initially before declining (103). The main ROS that harm proteins, lipid membranes and DNA include H_2O_2, hydroxyl radicals ($\cdot$OH), (O_2^-) and singlet oxygen ($^1O_2$). In addition to impairing cellular function, lipid peroxidation of organelles and cell membrane enzymes cause membrane leakage and autolysis (109). Research is conducted worldwide to improve the plant's efficiency in responding to environmental cues and increasing production.

Effect of salt stress on the metabolome of Solanaceae family

Today, salinity is a significant global problem that affects agricultural productivity. High salinity affects approximately 33 % of irrigated agricultural lands globally and these regions are increasing by 10 % per year (110). Ionic and osmotic stresses are the two major threats of salinity (111). Regions with naturally saline soil, irrigation with saline water, or seawater infiltration can cause soil that supports plant growth in coastal locations to become saline (112). Salinity is becoming a serious threat because of global warming. The sensitivity of plants to salinity varies greatly across growth stages (113). The stages that are most negatively impacted by salinity are seed germination and the seedling stage. Plant metabolism is greatly affected by salinity due to the ionic imbalance (114). When the soil's salt concentration rises and the water potential falls, the plant cell's pressure potential declines and the cell eventually stop dividing and elongating (115). Salt stress has a negative effect on multiple physicochemical processes in plants, such as photosynthesis, transpiration, etc. and it also affects the growth of vegetative and reproductive organs (116). Reactive oxygen species also increases in plants in response to salinity (117). With increasing soil salinity, germination percentage, germination time, dry weight and root shoot ratio of pepper, tomato, eggplant and seed and seedling of other glycophytic plants are severely affected (88, 89, 118–120). It alters plant ion concentrations and ultimately leads to the formation of ROS. Sodium ion (Na^+) influx causes the efflux of the potassium ion (K^+), which leads to the disturbance in the concentration of Ca^{+2} ion in capsicum (121). Potato salinity alters Mg^{2+} ion concentration in leaves, leading to stomatal closure. Sodium and chloride (Cl^-) ions reduce chlorophyll content (122). Sodium, calcium (Ca), K and Mg uptake in plant tissues under salinity stress is genotype-dependent (116). There is a notable reduction in the concentration of K, Ca and Mg ions with increases in salt concentration in pepper (109). In case of tomatoes, the administration of Ca^{+2} ions somewhat mitigates the effects of salinity (123). In potato, K+ concentration in leaves declined with increasing salt levels, whereas it increased in stems and tubers (124). Proline is the primary osmolyte that accumulates when plants experience salt stress and it helps provide tolerance. Amount of proline accumulation differs across genotype, developmental stage and organs of plant. Proline also serves as an antioxidant, a stabiliser of subcellular structures, a regulator of cell redox homeostasis, a source of energy and a signaling molecule (125). In potato plant highest accumulation of proline is in stem tissue (126). The concentration of soluble protein in potato leaves drastically decreased in salt stress (127). Tobacco varieties subjected to salt stress showed a rise in the total amount of protein in comparison to the leaves of plants under control (128). Polyamines are also important molecules that play protective, regulatory and ROS-scavenging roles (129). Level of putrescine, spermidine and spermine increased significantly under salinity stress in tomato cultivars (93). To counteract the oxidative stress plant has antioxidant system which includes both enzymatic and non-enzymatic antioxidants. Some of the major enzymatic antioxidants are SOD, POD, CAT and Glutathione Reductase (GR). Some non-enzymatic antioxidants include flavonoids, carotenoids, vitamin C and vitamin D. Levels of antioxidants in plants are genotype- and organ-dependent. Malondialdehyde and H_2O_2 are indicators of oxidative stress. As the concentration of salt increases, the levels of MDA and H_2O_2 also increase in tomato (130) and similar results were observed in potato (131) and capsicum (90). In huckleberry there is no significant change in MDA content but in eggplant it increased markedly (91). Plants with higher levels of antioxidants show greater tolerance to salinity than plants with lower levels of antioxidants in the cell. Salt-resistant varieties showed increased overall phenolic levels (132). In eggplant leaves, CAT activity increases, whereas in roots it decreases. Glutathione reductase activity increases in huckleberry roots, whereas in leaves there is no significant change (91). In some potato cultivars, SOD activity increases and CAT activity decreases (133). High concentration of salt boosts up activity of ROS-scavenging enzymes like CAT, Ascorbate Peroxidase (APX) and GR in salt-tolerant potato cultivars (99). Salinity has a significant effect on the amount and nutritional value of the fruit, delaying flowering and fruit ripening. In pepper fruit, the number and size decrease, whereas the capsaicinoid content increases and Vitamin B_6, Vitamin B_{12} and Vitamin C decreased (86). In tomato fruits, osmotic and water potentials were reducedand the fruit cuticle's water permeability decreased (134). With the growing population it becomes necessary to make stress tolerant varieties to fulfill the needs of the world. Red pepper becomes tolerant when proline and l-tryptophan are applied exogenously in combination (89). N-supplementation lessens the detrimental effects of salt on agricultural production (135). Application of Se on the leaves can increase the tolerance in eggplant against salt stress (136). Salicylic acid and GSH play significant roles in conferring salinity tolerance in tomato (93, 137).

Effect of temperature stress on the metabolome of the Solanaceae family

The most vital abiotic factor affecting all organisms' life processes is temperature. Temperature is a significant environmental variable that varies with the seasons and undergoes periodic fluctuations. Consequently, plant cells must be able to detect changes in the surrounding temperature and convert this information into flexible physiological responses. The mechanisms governing intracellular temperature signaling are essential for regulating the emergence of resistance to heat or cold stress under severe temperature conditions (138). The three different forms of temperature stress that plants typically undergo are (a) chilling stress (occurs during below freezing temperature), (b) freezing stress (occurs during above freezing temperature) and (c) heat stress. This demonstrates how plants' physiological and metabolic processes are affected by both low and high temperatures and the effects of the plant's resistance to high and low temperatures or the potential for adaptability (139). Temperature, as well as other environmental factors (e.g., light, nutrients and moisture), has a significant impact on how tomato plants respond during the vegetative and reproductive phases. Various studies have shown the detrimental effect of environmental changes, such as high or low temperature stress on the tomato growth. The rates of various biological processes are influenced by temperature, which is also a critical factor in tomato fruit development (140). Tomato plants can also withstand a broad range of temperatures; it has long been known that high daytime temperatures negatively affect fruit yield when temperatures exceed 32 °C, especially when nighttime temperatures exceed 21 °C. For the tomato, extreme temperature stress at 30 °C and 45 °C has been shown to significantly reduce anthesis, blossom drop and fruit set. Critical pre-anthesis high-temperature stress was associated with reduced pollen production, epidermal and endothecial abnormalities and other developmental alterations in the anther (141). The photosynthetic system is severely damaged by high-temperature stress (140).There are a number of manifestations that prevent tomato fruit from setting at high temperatures, including: underdeveloped flowers, bud drop, poor fertilization, style elongation, slowdown of pollen tube growth, reduction in carbohydrate availability, sugar metabolism is slowed and viable pollen generation is ineffective, abortion of the ovule and endosperm deterioration. The influence of a rather low nighttime temperature of 13 °C for optimal tomato fruit set had already been noted long before and this phenomenon was known as thermos-periodism. Subsequently, research in the phytotron established that lowering nighttime temperature by 15–20 °C significantly increased the biological and commercial production of tomatoes (141). Tomato metabolism can be significantly altered by exposure to elevated temperatures. In tomato plants cultivated at high temperatures (35 °C), H_2O_2 accumulates and cannot be removed by the GSH/ascorbate cycle, as the same high temperature may have rendered its primary enzymes inactive. This buildup of H_2O_2 would initially decrease foliar biomass before killing the plant. On the other hand, tomato plants cultivated at the optimal temperature (25 °C) develop effectively, exhibiting efficient active oxygen species (AOS) detoxification and, consequently, proper functioning of the plant's antioxidant systems (142). During fruit development, isocitrate levels fluctuate during post-harvest storage. At high temperatures, pollen development becomes sensitive and pollen viability declines, a reduction linked to decreases in metabolites such as PAS and carbohydrates (36). During low temperature, sugars, phenolic substances accumulate i.e., flavonoid content increases, whereas other metabolites like SA, ABA and raffinose content also increase, amino acid content, i.e., leucine, isoleucine, valine, phenylalanine and alanine, decreases (143). Early planting conditions in the north-western plains and India are limited by the adoption of potatoes due to high temperatures during crop growth and tuberization. Potato quality and yield are highly sensitive to high temperatures (144). Potato has temperature needs i.e., the optimal and limit values for growth of the above-ground portion and for tubers are different. In potatoes, hilum growth occurs at a rate of 20 to 25 °C, whereas 15 to 20 °C is the optimal temperature for tuber growth and tuberisation. Reduction in the potato tuberisation and acceleration in the growth of plants above ground parts occur at temperatures greater than those considered appropriate (145). When the temperature is low, it favours tuberisation, which is reduced during nighttime temperatures over 20 °C and is completely inhibited at temperatures over 25 °C. The two main processes for dealing with abiotic stresses are melatonin-mediated ROS scavenging and activation of the antioxidant defense response. Furthermore, it functions as a key regulator of plant defense mechanisms in response to environmental stresses by regulating genes associated with pathogenesis, antioxidant enzymes and stress-specific genes (146). During daytime temperature enzymes like fumarate, citrate and fumarate decreases in tubers as well as in leaves. At high temperature, photosynthetic capacities of leaves are enhanced and there is a decrease in the tuber and leaf content of the amino acids (147). Even the starch accumulation and photosynthesis capacity decreases because of the loss of chlorophyll content and carbon transport inhibition. Several metabolites, i.e., amino acids like histidine, as well as N-containing compounds and hormones, include JA decreases (28). In temperate locations, sweet peppers are cultivated as an annual crop. The ideal temperature for sweet pepper growth is between 20 and 25 °C. Growth is typically slowed down and yield is reduced when temperature goes below 15°C or rises over 32°C (148). Warm temperatures (between 21 and 29 °C), wet soil and moderate temperatures are ideal growing conditions for bell peppers. Low temperature is an environmental condition that significantly affects plant growth, including photosynthesis, water uptake and nutrient uptake. Crops with such economic importance as pepper, which influences the yield as well as the quality of such crops (149). During low temperature, SA significantly reduced MDA content and $(O2^{\bullet})$ production. Even before the onset of heat stress, SA treatment enhanced O_2 scavenging, POD activity and GSH accumulation (150–153). High levels of metabolites, i.e., sugars, PAS and amino acids, i.e., proline, increase considerably during low temperature (154). On the other hand, plants' responses to high temperatures are significantly influenced by the intricate metabolic regulatory networks. High temperature reorganises the metabolic state to maintain homeostasis. For instance, the high temperature is influenced by proteins, free proline, glycinebetaine, soluble carbohydrates, phenolic substances and lipids. These metabolites also help plants produce metabolites in response to heat stress by maintaining osmotic balance and conferring HS tolerance. Main osmotic adjusting materials in plants i.e. amount of protein, proline and total soluble sugars are enhanced. Flavonoids act like antioxidants to eliminate the ROS produced by the HS, that play the essential role in treating the HS response. MDA content rises as well (32). The ideal temperature for *Nicotiana Tabacum* L. throughout its field growing phase is between 22 and 28 °C and during its mature stage, the temperature shouldn't drop 20 °C below because of its sensitivity to low temperatures. When temperature falls below 10 to 13 °C, tobacco plants are unable to grow and at 2 to 3 °C, plants will die (155). Numerous tightly controlled metabolic networks in plants can be crucial to their growth when exposed to the low temperature. It has been studied that the exposure to the cold triggers the expression and/or activation of numerous metabolic processes. Since they are necessary for essential proteins production and also form the wide range of metabolic products with numerous roles in the responses of plants. For e.g. amino acids are well as the sugars are recognized during low temperature. The content of amino acids i.e. serine, valine, tyrosine, leucine and L-aspartate increase in greater amount. Hormones such as gibberellin, ethylene, auxin and ABA are regulated during low temperature (156). Majority of tropical vegetables as well as fruits including the brinjal, are sensitive. Less than 10 °C, brinjal plant experience physiologic problems that are primarily shown by the development of external wounds like scalding and pitting, browning of the flesh as well as the seed darkening (157). The range of 22 to 28 °C is ideal for the growth and development of eggplant (158). During the cool season, when temperature stress is low in brinjal, the loss of pollen fertility occurs, as well as the parthenocarpic fruit formation, but the female fertility is not affected at all. Effect of the temperature on the male sterility is transient and normal seed development restores full pollen fertility as temperature conditions improve (159). During high temperature stress, it often causes an increase in the production of ROS like H_2O_2, $(^1O_2)$, $\cdot OH$ as well as $(O_2^{\bullet -})$ all of which can cause the denaturation of the proteins, damage to the nucleic acid and the lipid peroxidation and nucleic acid damage in brinjal. To confront the ROS damage, plants have generated the enzymatic system and as well as Brassinosteroids are type of essential steroidal plant growth regulator that promote germination of seed, elongation of the cell and cell division in brinjal (160).

Studies report that young leaves and developing reproductive organs contain a range of biochemicals like organic and amino acids, nitrogen-containing compounds, lipids and secondary metabolites, which enable the plant for defense mechanisms (161).

In another study, a cross-cultivar comparison between various pepper cultivars (*Capsicum annuum* cv.) using LC-MS and a cross-species comparison of fruit-metabolomics to clarify the metabolic regulation of fruit polyphenolics from three representative crops of Solanaceae (tomato, eggplant and pepper), a metabolic trade-off between flavonoids and hydroxycinnamates in anthocyanin-type and spicy pepper cultivars and found fruit polyphenolic metabolic signatures in each species from various tissue types and fruit ripening stages (28).

In an experiment to elucidate the physiological and biochemical processes of tomato plants' leaves as well as their flower and fruit set throughout the reproductive stage under waterlogging stress in six genotypes of tomato it shows that height of plant, diameter of stem, number of inflorescences, weight of single fruit and per plant are significantly affected negatively under water logging in addition to chlorophyll content, low net photosynthetic rate, low diffusion of gas and impaired rate of transpiration and antioxidant system. The study also reports elevated MDA and H_2O_2 levels across all screened genotypes under stress (162).

To identify eggplant cultivars that withstand waterlogging and are suitable for summer growth, a field experiment was conducted with 10 genotypes. It was found that the variety BARI Hybrid Begun-6 demonstrated superior performance compared to other varieties and lines and appears promising for the summer season (103).

Integrated approaches

To address the issue comprehensively, an integrated research approach that combines multiple disciplines, methodologies and data sources is essential. There are numerous reports on integrated "omics" approaches to elucidate abiotic stress tolerance mechanisms in Solanaceae species.

An integrated "omics" approach (physiology, metabolites, mRNAs and promoters) to drought stress responses in tobacco and other common Solanaceae members (tomato and potato) revealed that many drought responses are family- and species-specific (163).

The pathogenesis–related protein 1 (PR-1) gene family is reported to play a crucial role in plant biotic and abiotic stress responses and metabolism. Scientists reported a study on the PR-1 gene family in *S. lycopersicum* L., which identified 13 novel SlPR-1 genes. Bioinformatics analysis (KEGG annotation) of this study showed that the SlPR-1 proteins worked in the environmental information processing (09130) (164).

A compilation report on genomics, proteomics and metabolomics research to enhance the abiotic stress tolerance of the tomato plant was published recently (165). RNA–seq studies of *S. melongena* and its wild relative (*S. dasyphyllum*) under various osmotic stress conditions revealed that *S. dasyphyllum* is an excellent genetic resource for breeding experiments for stress-tolerant eggplant varieties (87).

A group of researchers reported the tissue-specific modulation in gene expression of key genes and pathways associated with various proteins under high temperature stress in various parts of the sweet potato (leaf, tuberous roots, fibrous roots) (166). A comparative study to analyse the response of aerial and ground parts of *H. annuus* and *S. lycopersicum* in Na^+ and K^+ intake during salt stress (NaCl) reveals that in both the plants, the concentration of melatonin increases as in direct proportion to the intensity of salinity stress and Na^+ and $K^+$are accumulated in roots and stem in *H. annuus* but in fruits and roots in *S. lycopersicum*. In this study the very low-level K^+ was reported in seeds of *H. annuus* and fruit and root of *S.lycopersicum* (142).

Genomic studies report the list of genes and gene families involved in the drought stress tolerance in Solanaceae members. Tissue-specific transcriptomic responses were reported from the leaves and roots of Petunia hybrid Mitchell under salt stress (167). Expression analysis study of tomato ammonium transporters 1 (SlAMT1) genes under osmotic stress (drought and salinity stress) was reported by researchers. The study shows variation in SlAMT1s at both the nucleotide and protein levels. The study concludes that the SlAM1-3 genes exhibited distinct expression patterns compared with others. This study further demonstrates that abiotic stress conditions negatively affect SlAMT1 expression (168).

Phenotypic analysis of trichomes in *Solanum* species, under field conditions, reveals increased trichome density and stomatal size under water-deficit conditions (169). In a study, HPLC coupled to high-resolution mass spectrometry (HRMS) allowed the identification of more than 200 metabolites in *Nicotiana langsdorffii* Weinm. under exposure to different abiotic stress conditions, viz., water deficit, high temperature and high chromatin concentration (170).

Conclusion

With increasing population, demand has also risen; therefore, it is necessary to increase production to meet people's needs. But increasing global warming, low rainfall and soil degradation caused by excessive fertiliser use and other factors affect plant growth, reducing productivity and yield. The plant responds to different stresses by altering metabolite concentrations across tissues, thereby enhancing resistance. These metabolites help to counteract the stress condition. More than one lakh metabolites are present in plants which include both primary and secondary metabolites. But with the existing technology, we are able to identify only a few metabolites rest are still unknown to mankind. Advancements in technology and improvements to existing methods are needed to identify metabolites with greater precision. The phenotype of a plant can be predicted by integrating both genomics and metabolomics, which is helpful in crop breeding. Like proline and SA, many more chemical compounds can be identified that help plants withstand harsh stressful conditions. Since the Solanaceae family members are important and have nutraceutical values so their resistant varieties should be developed. With the help of metabolomics, it can be studied which development stage and which organ of the plant is more affected due to stress so farmers can take necessary actions to minimise the effect of stress.

There are several critical gaps in metabolomics research on Solanaceae that remain fragmented and incomplete, despite extensive research on physiological and transcriptomic studies in Solanaceae crops (tomato, potato, pepper, eggplant, tobacco). Many existing studies are stress, tissue, or genotype-specific, which limits cross–species comparisons and interferes with the identification of conserved, stress–responsive metabolic features across the family. Because of the limited spectral libraries and compound annotations, specialised secondary metabolites - particularly alkaloids, phenolics and GAs are poorly resolved. The current studies are based on the metabolic analyses at a single time point in abiotic stress interaction, ignoring the dynamic metabolic reprogramming during stress perception, acclimation and recovery.

Genes and metabolite accumulation cannot be causally inferred because integration with genomics, transcriptomics, proteomics and fluxomics remains uncommon. Furthermore, environmentally realistic stress combinations (e.g. heat-drought, salinity-nutrient stress) and root-shoot metabolite cross-talk remain underexploited still. The lack of standardized experimental designs, metabolite databases specific to Solanaceae and field-level validation limits translational application for breeding abiotic stress-resilient cultivars.

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Authors' contributions

VDN conceived the idea, designed the study and edited the manuscript. RT, MS and S wrote the first draft of the manuscript. SA formatted the final draft for journal submission. JJ thoroughly reviewed the manuscript. KCS designed the figures. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

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Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this word, the authors used Napkin AI in order to paraphrase/correct grammatical mistakes and python code generation, respectively. After using this tool/service, the authors reviewed and edited the content as needed and takes full responsibility for the content of the published article.

References

1. Rigano M, De Guzman G, Walmsley A, Frusciante L, Barone A. Production of pharmaceutical proteins in Solanaceae food crops. Int J Mol Sci. 2013;14(2):2753–73. https://doi.org/10.3390/ijms14022753
2. Gebhardt C. The historical role of species from the Solanaceae plant family in genetic research. Theor Appl Genet. 2016;129(12):2281–94. https://doi.org/10.1007/s00122-016-2804-1

3. Mukasa-Tebandeke IZ, Karume I, Ssebuwufu J, Wasajja HZ, Nankinga RM. Comparison of antioxidant flavonoid and polyphenol content of three selected Solanaceae genera from Kigezi, Southwest Uganda. Int J Chem Mater Sci. 2022;5(4):40–60. https://doi.org/10.36348/sijcms.2022.v05i04.001
4. Añibarro-Ortega M, Pinela J, Alexopoulos A, Petropoulos SA, Ferreira ICFR, Barros L. The powerful Solanaceae: food and nutraceutical applications in a sustainable world. Adv Food Nutr Res. 2022;100:131–72. https://doi.org/10.1016/bs.afnr.2022.03.004
5. Hančinský R, Mihálik D, Mrkvová M, Candresse T, Glasa M. Plant viruses infecting Solanaceae family members in cultivated and wild environments: a review. Plants. 2020;9(5):667. https://doi.org/10.3390/plants9050667
6. Zhu JK. Abiotic stress signaling and responses in plants. Cell. 2016;167(2):313–24. https://doi.org/10.1016/j.cell.2016.08.029
7. Hong J, Yang L, Zhang D, Shi J. Plant metabolomics: an indispensable systems biology tool for plant science. Int J Mol Sci. 2016;17(6):767. https://doi.org/10.3390/ijms17060767
8. Hall RD, Brouwer ID, Fitzgerald MA. Plant metabolomics and its potential application for human nutrition. Physiol Plant. 2008;132:162–75. https://doi.org/10.1111/j.1399-3054.2007.00989.x
9. Scossa F, Brotman Y, de Abreu e Lima F, Willmitzer L, Nikoloski Z, Fernie AR. Genomics-based strategies for the use of natural variation in the improvement of crop metabolism. Plant Sci. 2016;242:47–64. https://doi.org/10.1016/j.plantsci.2015.05.021
10. Hegeman AD. Plant metabolomics—meeting the analytical challenges of comprehensive metabolite analysis. Brief Funct Genomics. 2010;9:139–48. https://doi.org/10.1093/bfgp/elp053
11. Okazaki Y, Saito K. Recent advances of metabolomics in plant biotechnology. Plant Biotechnol Rep. 2012;6:1–15. https://doi.org/10.1007/s11816-011-0191-2
12. Khakimov B, Bak S, Engelsen SB. High-throughput cereal metabolomics: current analytical technologies, challenges and perspectives. J Cereal Sci. 2014;59:393–418. https://doi.org/10.1016/j.jcs.2013.10.002
13. Shulaev V, Cortes D, Miller G, Mittler R. Metabolomics for plant stress response. Physiol Plant. 2008;132:199–208. https://doi.org/10.1111/j.1399-3054.2007.01025.x
14. Marciniak P, Kolińska A, Spochacz M, Chowański S, Adamski Z, Scrano L, et al. Differentiated effects of secondary metabolites from Solanaceae and Brassicaceae plant families on the heartbeat of *Tenebrio molitor* pupae. Toxins. 2019;11:287. https://doi.org/10.3390/toxins11050287
15. Cárdenas PD, Sonawane PD, Heinig U, Bocobza SE, Burdman S, Aharoni A. The bitter side of the nightshades: genomics drives discovery in Solanaceae steroidal alkaloid metabolism. Phytochemistry. 2015;133:24–32. https://doi.org/10.1016/j.phytochem.2014.12.010
16. Xue Z, Duan LX, Qi X. Gas chromatography mass spectrometry coupling techniques. In: Qi X, Chen X, Wang Y, editors. Plant Metabolomics: Methods and Applications. Dordrecht: Springer; 2014. https://doi.org/10.1007/978-94-017-9291-2_2
17. García-Valencia LE, Valiente-Banuet JI, Trevino V, Díaz de la Garza RI, Rodríguez-López C. Untargeted metabolomics unveils the edaphic stress impact on habanero pepper ripening fruit. ACS Agric Sci Technol. 2023;3:33–44. https://doi.org/10.1021/acsagscitech.2c00132
18. Jimenez-García SN, Garcia-Mier L, Ramirez-Gomez XS, Guevara-Gonzalez RG, Aguirre-Becerra H, Escobar-Ortiz A, et al. Characterization of key compounds of bell pepper by spectrophotometry and gas chromatography under induced stress. Molecules. 2023;28:3830. https://doi.org/10.3390/molecules28093830
19. Zhang J, Liang L, Xie Y, Zhao Z, Su L, Tang Y, et al. Transcriptome and metabolome analyses reveal molecular responses of two pepper (*Capsicum annuum* L.) cultivars to cold stress. Front Plant Sci. 2022;13:819630. https://doi.org/10.3389/fpls.2022.819630
20. Thorat SA, Srivaishnavi M, Kaniyassery A, Padikkal S, Rai PS, Botha A, et al. Physiological and biochemical traits modulate tissue-specific withanolides and untargeted metabolites in *Withania somnifera* under salinity stress. Plant Physiol Biochem. 2023;203:108011. https://doi.org/10.1016/j.plaphy.2023.108011
21. Merino I, Guasca AO, Krmela A, Arif U, Ali A, Westerberg E, et al. Metabolomic and transcriptomic analyses identify external conditions underlying toxic glycoalkaloid accumulation in potato tubers. Front Plant Sci. 2023;14:1210850. https://doi.org/10.3389/fpls.2023.1210850
22. Li D, Zhou C, Li JQ, Dong Q, Miao P, Lin Y, et al. Metabolomic analysis on the mechanism of nanoselenium alleviating cadmium stress and improving the pepper nutritional value. J Nanobiotechnol. 2022;20:523. https://doi.org/10.1186/s12951-022-01739-5
23. Reimer JJ, Shaaban B, Drummen N, Ambady SS, Genzel F, Poschet G, et al. *Capsicum* leaves under stress: using multi-omics analysis to detect abiotic stress network of secondary metabolism in two species. Antioxidants. 2022;11(4):671. https://doi.org/10.3390/antiox11040671
24. Raletsena MV, Mdlalose S, Bodede OS, Assress HA, Woldesemayat AA, Modise DM. 1H-NMR and LC-MS based metabolomics analysis of potato (*Solanum tuberosum* L.) cultivars irrigated with fly ash-treated acid mine drainage. Molecules. 2022;27:1187. https://doi.org/10.3390/molecules27041187
25. Sun H, Li Q, Mao LZ, Yuan QL, Huang Y, Chen M, et al. Investigating the molecular mechanisms of pepper fruit tolerance to storage via transcriptomics and metabolomics. Horticulturae. 2021;7:242. https://doi.org/10.3390/horticulturae7080242
26. Liu B, Kong L, Zhang Y, Liao Y. Gene and metabolite integration analysis through transcriptome and metabolome brings new insight into heat stress tolerance in potato (*Solanum tuberosum* L.). Plants. 2021;10:103. https://doi.org/10.3390/plants10010103
27. Reimer JJ, Thiele B, Biermann RT, Junker-Frohn LV, Wiese-Klinkenberg A, Usadel B, et al. Tomato leaves under stress: a comparison of stress response to mild abiotic stress between a cultivated and a wild tomato species. Plant Mol Biol. 2021;107:177–206. https://doi.org/10.1007/s11103-021-01194-0
28. Calumpang CLF, Saigo T, Watanabe M, Tohge T. Cross-species comparison of fruit metabolomics to elucidate metabolic regulation of fruit polyphenolics among solanaceous crops. Metabolites. 2020;10(5):209. https://doi.org/10.3390/metabo10050209
29. Xu J, Zhou Y, Xu Z, Chen Z, Duan L. Combining physiological and metabolomic analysis to unravel the regulations of coronatine alleviating water stress in tobacco (*Nicotiana tabacum* L.). Biomolecules. 2020;10:99. https://doi.org/10.3390/biom10010099
30. Wang J, Lv J, Liu Z, Liu Y, Song J, Ma Y, et al. Integration of transcriptomics and metabolomics for pepper (*Capsicum annuum* L.) in response to heat stress. Int J Mol Sci. 2019;20(20):5042. https://doi.org/10.3390/ijms20205042.
31. Gao XX, Locke S, Zhang JZ, Joshi J, Wang-Pruski G. Metabolomics profile of potato tubers after phosphite treatment. Am J Plant Sci. 2018;9:845–64. https://doi.org/10.4236/ajps.2018.94065
32. Singh R, Gupta P, Khan F, Singh SK, Sanchita, Mishra T, et al. Modulations in primary and secondary metabolic pathways and adjustment in physiological behaviour of *Withania somnifera* under drought stress. Plant Sci. 2018;272:42–54. https://doi.org/10.1016/j.plantsci.2018.03.029
33. Mibei EK, Owino WO, Ambuko J, Giovannoni JJ, Onyango AN. Metabolomic analyses to evaluate the effect of drought stress on selected African eggplant accessions. J Sci Food Agric. 2015;98(1):205–16. https://doi.org/10.1002/jsfa.8458
34. Paupière MJ, Müller F, Li H, Rieu I, Tikunov YM, Visser RG, et al. Untargeted metabolomic analysis of tomato pollen development and heat stress response. Plant Reprod. 2017;30(2):81–94. https://doi.org/10.1007/s00497-017-0301-6

35. Khondoker MG, Li H, Sivasithamparam K, Jones MGK, Du X, Ren Y, et al. Metabolic responses of endophytic *Nicotiana benthamiana* plants experiencing water stress. Environ Exp Bot. 2017;143:59–71. https://doi.org/10.1016/j.envexpbot.2017.08.008

36. Rabara RC, Tripathi P, Reese RN, Rushton DL, Alexander D, Timko MP, et al. Tobacco drought stress responses reveal new targets for Solanaceae crop improvement. BMC Genomics. 2015;16:484. https://doi.org/10.1186/s12864-015-1575-4

37. Scalabrin E, Radaelli M, Rizzato G, et al. Metabolomic analysis of wild and transgenic *Nicotiana langsdorffii* plants exposed to abiotic stresses: unraveling metabolic responses. Anal Bioanal Chem. 2015;407:6357–68. https://doi.org/10.1007/s00216-015-8770-7

38. Sung J, Sonn Y, Lee Y, Kang S, Ha S, Hari BK, et al. Compositional changes of selected amino acids, organic acids and soluble sugars in the xylem sap of N-, P-, or K-deficient tomato plants. J Plant Nutr Soil Sci. 2014;178(5):792–7. https://doi.org/10.1002/jpln.201500071

39. Ampofo-Asiama J, Baiye VMM, Hertog MLATM, Waelkens E, Geeraerd AH, Nicolai BM, et al. The metabolic response of cultured tomato cells to low oxygen stress. Plant Biol. 2014;16(3):594–606. https://doi.org/10.1111/plb.12094

40. Terras-Claveria L, Jáuregui O, Codina C, Tiburcio AF, Bastida J, Viladomat F. Analysis of phenolic compounds by high-performance liquid chromatography coupled to electrospray ionization tandem mass spectrometry.

41. in senescent and water-stressed tobacco. Plant Sci. 2012;182:71–8. https://doi.org/10.1016/j.plantsci.2011.02.009

42. Sánchez-Rodríguez E, Moreno DA, Ferreres F, Rubio-Wilhelmi MM, Ruiz JM. Differential responses of five cherry tomato varieties to water stress: changes on phenolic metabolites and related enzymes. Phytochemistry. 2011;72(8):723–9. https://doi.org/10.1016/j.phytochem.2011.02.011

43. Semel Y, Schauer N, Roessner U, Zamir D, Fernie AR. . Metabolite analysis for the comparison of irrigated and non-irrigated field grown tomato of varying genotype. Metabolomics. 2007;3:289–95. https://doi.org/10.1007/s11306-007-0055-5

44. Swartz ME. UPLC™: an introduction and review. J Liq Chromatogr Relat Technol. 2005;28(7–8):1253–63. https://doi.org/10.1081/JLC-200053046

45. Obata T, Fernie AR. The use of metabolomics to dissect plant responses to abiotic stresses. Cell Mol Life Sci. 2012;69(19):3225–43. https://doi.org/10.1007/s00018-012-1091-5

46. Kumari S, Stevens D, Kind T, Denkert C, Fiehn O. Applying in-silico retention index and mass spectra matching for identification of unknown metabolites in accurate mass GC-TOF mass spectrometry. Anal Chem. 2011;83(15):5895–902. https://doi.org/10.1021/ac2006137

47. Chen L, Zhou F, Chen Y, Fan Y, Zhang K, Liu Q, et al. Salicylic acid improves the constitutive freezing tolerance of potato as revealed by transcriptomics and metabolomics analyses. Int J Mol Sci. 2023;24:609. https://doi.org/10.3390/ijms24010609

48. Vanitha A, Kalimuthu K, Chinnadurai V, Sharmila Juliet Y, Prabakaran R. GCMS analysis of leaf and salt stress callus of eggplant (*Solanum melongena* L.). J Pharm Res Int. 2017;14(6):1-11. https://doi.org/10.9734/BJPR/2016/30425

49. Roy C, Maji SR, Ghose TK, Bhattacharya SG. Stress causing dynamic changes of four phytohormones in tobacco and tomato: a GC-MS analysis. Res Plant Biol. 2019;9(1):16–22. https://doi.org/10.25081/ripb.2019.v9.3753

50. Luengwilai K, Saltveit M, Beckles DM. Metabolite content of harvested Micro-Tom tomato (*Solanum lycopersicum* L.) fruit is altered by chilling and protective heat-shock treatments as shown by GC-MS metabolic profiling. Postharvest Biol Technol. 2012;63:116–22. https://doi.org/10.1016/j.postharvbio.2011.05.014

51. Lokesha AN, Shivashankara KS, Ravishankar KV, Geetha GA, Laxman RH, Roy TK, et al. Association of volatile terpenoids and their biosynthetic genes in high-temperature stress tolerance in tomato (*Solanum lycopersicum* L.). J Hortic Sci. 2024;19(2):1–8. https://doi.org/10.24154/jhs.v19i2.2254

52. Schripsema J. Application of NMR in plant metabolomics: techniques, problems and prospects. Phytochem Anal. 2010;21(1):14–21. https://doi.org/10.1002/pca.1185

53. Moco S, Bino RJ, Vorst O, Verhoeven HA, de Groot J, van Beek TA, et al. A liquid chromatography-mass spectrometry-based metabolome database for tomato. Plant Physiol. 2006;141(4):1205–18. https://doi.org/10.1104/pp.106.078428

54. Al Sinani SS, Eltayeb EA. The effect of salinity on solamargine and solasonine contents of *Solanum incanum* plants grown in Oman. SQU J Sci. 2014;19(2):1–7. https://doi.org/10.24200/squjs.vol19iss2pp1-7

55. Paul AT, Vir S, Bhutani KK. Liquid chromatography-mass spectrometry-based quantification of steroidal glycoalkaloids from *Solanum xanthocarpum* and effect of different extraction methods on their content. J Chromatogr A. 2008;1208(1–2):141–6. https://doi.org/10.1016/j.chroma.2008.08.089

56. Maurya A, Manika N, Verma RK, Singh SC, Srivastava SK. Simple and reliable methods for the determination of three steroidal glycosides in eight species of *Solanum* by reversed-phase HPLC coupled with diode array detection. Phytochem Anal. 2013;24(1):87–92. https://doi.org/10.1002/pca.2387

57. Jayanthi G, Senthilkumar T. LC-MS analysis of a potent medicinal plant Solanum nigrum L. variants black and orange fruits. Int J Bot Stud. 2023;8(4):16-9.

58. Ben-Abdallah S, Zorrig W, Amyot L, Renaud J, Hannoufa A, Lachâal M, et al. et al. Potential production of polyphenols, carotenoids and glycoalkaloids in *Solanum villosum* Mill. under salt stress. Biologia. 2019;74:309–24. https://doi.org/10.2478/s11756-018-00166-y.

59. Moreira GC, Anjos GL, Carneiro CN, Ribas RF, Dias FS. Phenolic compounds and photosynthetic activity in *Physalis angulata* L. (Solanaceae) in response to exogenous abscisic acid application. Phytochem Lett. 2020;40:96–100. https://doi.org/10.1016/j.phytol.2020.09.018

60. Popova I, Sell B, Pillai SS, Kuhl J, Dandurand L. High-performance liquid chromatography-mass spectrometry analysis of glycoalkaloids from underexploited *Solanum* species and their acetylcholinesterase inhibition activity. Plants. 2021;11:269. https://doi.org/10.3390/plants11030269

61. Giannarelli S, Muscatello B, Bogani P, Spiriti MM, Buiatti M, Fuoco R. Comparative determination of some phytohormones in wild-type and genetically modified plants by GC-MS and HPLC-MS/MS. Anal Biochem. 2010;398(1):60–8. https://doi.org/10.1016/j.ab.2009.10.038

62. Kitsios G, Doonan JH. Cyclin-dependent protein kinases and stress responses in plants. Plant Signal Behav. 2011;6(2):204–9. https://doi.org/10.4161/psb.6.2.14835

63. Krishnan P, Kruger NJ, Ratcliffe RG. Metabolite fingerprinting and profiling in plants using NMR. J Exp Bot. 2005;56(410):255–65. https://doi.org/10.1093/jxb/eri010

64. Ratcliffe RG, Shachar-Hill Y. Revealing metabolic phenotypes in plants: inputs from NMR analysis. Biol Rev. 2005;80(1):27–43. https://doi.org/10.1017/S1464793104006530

65. Pang X, Chen J, Li L, Huang W, Liu J. Deciphering drought resilience in Solanaceae crops: Unraveling molecular and genetic mechanisms. Biology. 2024;13(12):1076. https://doi.org/10.3390/biology13121076

66. Nemadodzi LE, Managa GM, Nemukondeni N. ^{1}H NMR-based analysis to determine the metabolomics profile of *Solanum nigrum* L. (black nightshade) grown in greenhouse versus open-field conditions. Metabolites. 2025;15(5):344. https://doi.org/10.3390/metabo15050344

67. Zhang J, Zhang Y, Du Y, Chen S, Tang H. Dynamic metabonomic responses of *Nicotiana tabacum* plants to salt stress. J Proteome Res. 2011;10(4):1904–14. https://doi.org/10.1021/pr101140n

68. Sorin C, Mariette F, Musse M, Leport L, Cruz F, Yvin J, et al. Leaf development monitoring and early detection of water deficiency by low-field NMR relaxation in *Nicotiana tabacum* plants. Appl Sci. 2018;8(6):943. https://doi.org/10.3390/app8060943

69. Li J, Cang Z, Jiao F, Bai X, Zhang D, Zhai R. Influence of drought stress on photosynthetic characteristics and protective enzymes of potato at seedling stage. J Saudi Soc Agric Sci. 2017;16(1):82–8. https://doi.org/10.1016/j.jssas.2015.03.001

70. Anithakumari AM. Genetic dissection of drought tolerance in potato. Wageningen: Wageningen University and Research; 2011.

71. Shi S, Fan M, Iwama K, Li F, Zhang Z, Jia L. Physiological basis of drought tolerance in potato under long-term water deficiency. Int J Plant Prod. 2015;9(2):305–20. https://doi.org/10.22069/IJPP.2015.2050

72. Mona SA, Hashem A, Abd-Allah EF, Alqarawi AA, Soliman DWK, Wirth S, et al. Increased drought resistance by *Trichoderma harzianum* correlates with elevated secondary metabolites and proline. J Integr Agric. 2017;16(8):1751–7. https://doi.org/10.1016/S2095-3119(17)61695-2

73. Ahanger MA, Hashem A, Abd-Allah EF, Ahmad P. Arbuscular mycorrhiza in crop improvement under environmental stress. In: Emerging technologies and management of crop stress tolerance. Academic Press; 2014. p. 69–95. https://doi.org/10.1016/B978-0-12-800875-1.00003-X

74. Hashem A, Abd-Allah EF, Alqarawi AA, Al-Huqail AA, Wirth S, Egamberdieva D. Interaction between arbuscular mycorrhizal fungi and endophytic bacteria enhances growth of *Acacia gerrardii* under salt stress. Front Microbiol. 2016;7:1089. https://doi.org/10.3389/fmicb.2016.01089

75. Ahmad P, Hashem A, Abd-Allah EF, Alqarawi AA, John R, Egamberdieva D, et al. Role of *Trichoderma harzianum* in mitigating NaCl stress in *Brassica juncea* L. Front Plant Sci. 2015;6:868. https://doi.org/10.3389/fpls.2015.00868

76. Jatav KS, Agarwal RM, Singh RP, Shrivastava M. Growth and yield responses of wheat (*Triticum aestivum* L.) to suboptimal water supply and potassium doses. J Funct Environ Bot. 2012;2(1):39–51. https://doi.org/10.5958/j.2231-1742.2.1.005

77. Ximénez-Embún MG, Castañera P, Ortego F. Drought stress in tomato increases performance of adapted and non-adapted *Tetranychus urticae*. J Insect Physiol. 2017;96:73–81. https://doi.org/10.1016/j.jinsphys.2016.10.015

78. Visentin I, Vitali M, Ferrero M, Zhang Y, Ruyter-Spira C, Novák O, et al. Low strigolactone levels in roots as part of systemic drought signaling in tomato. New Phytol. 2016;212(4):954–63. https://doi.org/10.1111/nph.14190

79. Desoky ESM, Merwad ARM, Rady MM. Natural biostimulants improve saline soil properties and salt-stressed sorghum performance. Commun Soil Sci Plant Anal. 2018;49(8):967–83. https://doi.org/10.1080/00103624.2018.1448861

80. Semida WM, Hemida KA, Rady MM. Sequenced ascorbate–proline–glutathione seed treatment enhances cadmium tolerance in cucumber transplants. Ecotoxicol Environ Saf. 2018;154:171–9. https://doi.org/10.1016/j.ecoenv.2018.02.036

81. Rady MO, Semida WM, Abd El-Mageed TA, Hemida KA, Rady MM. Glycine betaine foliar application enhances salinity tolerance in onion via antioxidative defense. Sci Hortic. 2018;240:614–22. https://doi.org/10.1016/j.scienta.2018.06.069

82. Yang KY, Doxey S, McLean JE, Britt D, Watson A, Al Qassy D, et al. Root morphology remodeling by CuO and ZnO nanoparticles affects drought tolerance in plants colonized by beneficial *Pseudomonas*. Botany**.** 2018;96(3):175–186. https://doi.org/10.1139/cjb-2017-0124

83. Semida WM, Abdelkhalik A, Mohamed GF, Abd El-Mageed TA, Abd El-Mageed SA, Rady MM, et al. Zinc oxide nanoparticles enhance drought tolerance in eggplant (*Solanum melongena* L.). Plants (Basel). 2021;10(2):421. https://doi.org/10.3390/plants10020421

84. Lagat SK. Evaluation of African eggplant accessions for phenotypic traits and adaptation to water stress [MSc thesis]. Nairobi: University of Nairobi; 2016.

85. Ranaweera GKMMK, Fonseka RM, Fonseka H. Morpho-physiological and yield traits of interspecific hybrids of *Solanum melongena* L. under drought stress. Int J Minor Fruits Med Aromat Plants. 2020;6(1):30–37.

86. Hassani-Kakhki M, Karimi J, El Borai F, Killiny N, Hosseini M, Stelinski L, et al. Drought stress impairs communication between *Solanum tuberosum* and subterranean biological control agents. Ann Entomol Soc Am. 2020;113(1):23–29. https://doi.org/10.1093/aesa/saz050

87. Flores-Saavedra M, Plazas M, Vilanova S, Prohens J, Gramazio P. Induction of water stress in major *Solanum* crops: methodologies for identifying drought-tolerant materials. Sci Hortic. 2023;318:112105. https://doi.org/10.1016/j.scienta.2023.112105

88. Dong S, Ling J, Song L, Zhao L, Wang Y, Zhao T. Transcriptomic profiling of tomato leaves identifies novel factors responding to dehydration stress. Int J Mol Sci. 2023;24(11):9725. https://doi.org/10.3390/ijms24119725

89. Roldan MVG, Engel B, de Vos RCH, Vereijken P, Astola L, Groenenboom M, et al. Metabolomics reveals organ-specific metabolic rearrangements during early tomato seedling development. Metabolomics. 2014;10(5):958-74. https://doi.org/10.1007/s11306-014-0625-2

90. Prabhavathi V, Yadav JS, Kumar PA, Rajam MV. Abiotic stress tolerance in transgenic eggplant (*Solanum melongena* L.) expressing bacterial mannitol-1-phosphate dehydrogenase. Mol Breed. 2002;9(2):137–147. https://doi.org/10.1023/A:1026765026493

91. Khazaei Z, Estaji A. Foliar ascorbic acid application improves drought tolerance in sweet pepper (*Capsicum annuum*). Acta Physiol Plant. 2020;42(7):1–12. https://doi.org/10.1007/s11738-020-03106-z

92. Obidiegwu JE, Bryan GJ, Jones HG, Prashar A. Coping with drought: adaptive responses in potato and perspectives for improvement. Front Plant Sci. 2015;6:542. https://doi.org/10.3389/fpls.2015.00542

93. López-Serrano L, Canet-Sanchis G, Vuletin Selak G, Penella C, San Bautista A, López-Galarza S, et al. Pepper rootstock and scion physiological responses under drought stress. Front Plant Sci. 2019;10:38. https://doi.org/10.3389/fpls.2019.00038

94. Mane SP, Robinet CV, Ulanov A, Schafleitner R, Tincopa L, Gaudin A, et al. Molecular and physiological adaptation to prolonged drought in Andean potato leaves. Funct Plant Biol. 2008;35(8):669–688. https://doi.org/10.1071/FP07293

95. Vasquez-Robinet C, Mane SP, Ulanov AV, Watkinson JI, Stromberg VK, De Koeyer D, et al. Physiological and molecular adaptations to drought in Andean potato genotypes. J Exp Bot. 2008;59(8):2109–2123. https://doi.org/10.1093/jxb/ern073

96. Parry MAandralojc PJ, Scales JC, Salvucci ME, Carmo-Silva AE, Alonso H, et al. Rubisco activity and regulation as targets for crop improvement. J Exp Bot. 2013;64(3):717–730. https://doi.org/10.1093/jxb/ers336

97. Muhammad AA. Waterlogging stress in plants: a review. Afr J Agric Res. 2012;7(13):1976–1981. https://doi.org/10.5897/AJARX11.084

98. Aldana F, García PN, Fischer G. Effect of waterlogging stress on growth, development and symptomatology of cape gooseberry (*Physalis peruviana* L.). Rev Acad Colomb Cienc Exact Fis Nat. 2014;38(149):393–400. https://doi.org/10.18257/raccefyn.114

99. Adis MJ, Chavez CA, Prieto MC, Revollar Ochatoma PA, Vidoz ML, Mignolli F, et al. Unveiling flooding tolerance in eggplant (*Solanum melongena* L.): insights into biomass allocation, photosynthetic resilience and antioxidant defence strategies. Plant Soil. 2025;515:1765-79. https://doi.org/10.1007/s11104-025-07688-w

100. Bhatt RM, Laxman RH, Singh TH, Divya MH, Srilakshmi, Nageswar

Rao ADDVS. Response of brinjal genotypes to drought and flooding stress. Veg Sci. 2014;41(2):116–124.

101. Umicevic S, Kukavica B, Maksimovic I, Gasic U, Milutinovic M, Antic M, et al. Stress response in tomato influenced by repeated waterlogging. Front Plant Sci. 2024;15:1331281. https://doi.org/10.3389/fpls.2024.1331281

102. Kumar A, Kumari D, Adarsh A, Solankey SS. Advances in abiotic stresses management in potatoes. In: Solankey SS, editor. Advances in research on potato production. Cham: Springer; 2025. p. 297–343. https://doi.org/10.1007/978-3-031-82710-5_14

103. Gong X, Xu Y, Li H, et al. Antioxidant activation and ROS regulation promote waterlogging resistance in hot pepper (*Capsicum annuum* L.). BMC Plant Biol. 2022;22:25. https://doi.org/10.1186/s12870-022-03807-2

104. Sarker KK, Quamruzzaman AKM, Uddin MN, et al. Evaluation of eggplant (*Solanum melongena* L.) genotypes for short-term waterlogging tolerance. Gesunde Pflanzen. 2023;75:179–192. https://doi.org/10.1007/s10343-022-00688-1

105. Yin J, Niu L, Song X, Ottosen C, Wu Z, Jiang F, et al. Effect of waterlogging on morphology, physiology and fruit yield in tomato genotypes. Veg Res. 2023;3:0031. https://doi.org/10.48130/VR-2023-0031

106. Tejada-Alvarado JJ, Meléndez-Mori JB, Vilca-Valqui NC, Neri JC, Ayala-Tocto RY, Huaman-Huaman E, et al. Impact of wild Solanaceae rootstocks on morphological and physiological response, yieldand fruit quality of tomato (*Solanum lycopersicum* L.) grown under deficit irrigation conditions. Heliyon. 2023;9(1):e12755. https://doi.org/10.1016/j.heliyon.2022.e12755

107. Ahsan N, Lee DG, Lee SH, Kang KY, Bahk JD, Choi MS, et al. Comparative proteomic analysis of tomato leaves under waterlogging stress. Physiol Plant. 2007;131(4):555–70. https://doi.org/10.1111/j.1399-3054.2007.00980.x

108. Rasheed R, Iqbal M, Ashraf MA, Hussain I, Shafiq F, Yousaf A, et al. Glycine betaine alleviates waterlogging stress in tomato. J Hortic Sci Biotechnol. 2018;93(4):385–91. https://doi.org/10.1080/14620316.2017.1373037

109. Restrepo-Diaz H, Betancourt-Osorio J, Sanchez-Canro D. Nitrogen status and waterlogging effects on tamarillo seedlings. Not Bot Horti Agrobot Cluj-Napoca. 2016;44(2):375–81. https://doi.org/10.15835/nbha44210438

110. Anuradha M, Sivaraju K, Krishnamurthy V. Effect of waterlogging on physiological characteristics, yield and quality of flue-cured tobacco. Ind J Plant Physiol. 2013;18:67–70. https://doi.org/10.1007/s40502-013-0008-0

111. Kumar KM, Sujatha KB, Rajashree V, Kalarani MK. Gas exchange and antioxidant system in solanaceous species under waterlogging. J Agric Ecol. 2018;6:54–63. https://doi.org/10.53911/JAE.2018.6207

112. Singh H, Kumar P, Kumar A, Kyriacou MC, Colla G, Rouphael Y. Grafting tomato to improve salt tolerance. Agronomy. 2020;10(2):263. https://doi.org/10.3390/agronomy10020263

113. Giancarla V, Madoșă E, Ciulca S, Adriana C, Camen D, Iuliana C. Salinity stress effects in pepper (*Capsicum annuum* L.) cultivars. J Hortic For Biotechnol. 2020;24(1):61–64.

114. Hand MJ, Taffouo VD, Nouck AE, Nyemene KP, Tonfack B, Meguekam TL, et al. Effects of salt stress on plant growth, nutrient partitioning, chlorophyll content, leaf relative water content, accumulation of osmolytes and antioxidant compounds in pepper (*Capsicum annuum* L.) cultivars. Not Bot Horti Agrobo. 2017;45(2):481-90. https://doi.org/10.15835/nbha45210928

115. Kpinkoun JK, Amoussa AM, Mensah ACG, Komlan FA, Kinsou E, Lagnika L, et al. Effect of salt stress on flowering, fructification and fruit nutrients concentration in a local cultivar of chili pepper (*Capsicum frutescens* L.). Int J Plant Physiol Biochem. 2019;11(1):1–7. https://doi.org/10.5897/IJPPB2019.0284

116. De la Torre-González A, Montesinos-Pereira D, Blasco B, Ruiz JM. Influence of the proline metabolism and glycine betaine on tolerance to salt stress in tomato (*Solanum lycopersicum* L.) commercial genotypes. J Plant Physiol. 2018;231:329-36. https://doi.org/10.1016/j.jplph.2018.10.013

117. Yilmaz K, Akinci IE, Akinci S. Effect of salt stress on growth and Na, K contents of pepper (*Capsicum annuum* L.) in germination and seedling stages. Pak J Biol Sci. 2004;7(4):606-10. https://doi.org/10.3923/pjbs.2004.606.610

118. Jamil M, Kharal MA, Ahmad M, Abbasi GH, Nazli F, Hussain A, Akhtar MFZ. Inducing salinity tolerance in red pepper (*Capsicum annuum* L.) through exogenous application of proline and L-tryptophan. Soil Environ. 2018;37(2):160–8.

119. Shams M, Yildirim E, Arslan E, Agar G. Salinity induced alteration in DNA methylation pattern, enzyme activity, nutrient uptake and H_2O_2 content in pepper (*Capsicum annuum* L.) cultivars. Acta Physiol Plant. 2020;42(5):59. https://doi.org/10.1007/s11738-020-03053-9-

120. Assaha DVM, Liu L, Mekawy AMM, Ueda A, Nagaoka T, Saneoka H. Effect of salt stress on Na accumulation, antioxidant enzyme activities and activity of cell wall peroxidase of huckleberry (*Solanum scabrum*) and eggplant (*Solanum melongena*). Int J Agri Biol. 2015;17(6):1149–1156. https://doi.org/10.17957/IJAB/15.0052

121. Brenes M, Pérez J, González-Orenga S, Solana A, Boscaiu M, Prohens J, et al. Comparative studies on the physiological and biochemical responses to salt stress of eggplant (*Solanum melongena*) and its rootstock *S. torvum*. Agriculture. 2020;10(9):328. https://doi.org/10.3390/agriculture10080328

122. Zhou Y, Diao M, Chen X, Cui J, Pang S, Li Y, et al. Application of exogenous glutathione confers salinity stress tolerance in tomato seedlings by modulating ions homeostasis and polyamine metabolism. Sci Hortic. 2019;250:45–58. https://doi.org/10.1016/j.scienta.2019.02.026

123. Shumaila S, Ullah S. Mitigation of salinity-induced damages in *Capsicum annuum* L. (Sweet Pepper) seedlings using priming techniques. A future perspectives of climate change in the region. Commun Soil Sci Plant Anal. 2020;51(12):1602–25. https://doi.org/10.1080/00103624.2020.1791154

124. Chourasia KN, Lal MK, Tiwari RK, Dev D, Kardile HB, Patil VU, et al. Salinity stress in potato: understanding physiological, biochemical and molecular responses. Life (Basel). 2021;11(6):545. https://doi.org/10.3390/life11060545

125. Tanveer K, Gilani S, Hussain Z, Ishaq R, Adeel M, Ilyas N. Effect of salt stress on tomato plant and the role of calcium. J Plant Nutr. 2020;43(1):28–35. https://doi.org/10.1080/01904167.2019.1659324

126. Ghosh SC, Asanuma KI, Kusutani A, Toyota M. Effect of salt stress on some chemical components and yield of potato. Soil Sci Plant Nutr. 2001;47(3):467–75. https://doi.org/10.1080/00380768.2001.10408411

127. Al-Zubaidi AHA. Effects of salinity stress on growth and yield of two varieties of eggplant under greenhouse conditions. Res Crops. 2018;19(3):436–40. https://doi.org/10.31830/2348-7542.2018.0001.13

128. Jaarsma R, de Vries RSM, de Boer AH. Effect of salt stress on growth, Na+ accumulation and proline metabolism in potato (Solanum tuberosum) cultivars. PLoS One. 2013;8(3):e60183. https://doi.org/10.1371/journal.pone.0060183

129. Teixeira J, Fidalgo F. Salt stress affects glutamine synthetase activity and mRNA accumulation on potato plants in an organ-dependent manner. Plant Physiol Biochem. 2009;47(9):807–13. https://doi.org/10.1016/j.plaphy.2009.05.002

130. Çelik Ö, Atak Ç. The effect of salt stress on antioxidative enzymes and proline content of two Turkish tobacco varieties. Turk J Biol. 2012;36(3):339–56. https://doi.org/10.3906/biy-1108-11

131. Arbona V, Manzi M, Ollas CD, Gómez-Cadenas A. Metabolomics as a tool to investigate abiotic stress tolerance in plants. Int J Mol Sci. 2013;14(3):4885–911. https://doi.org/10.3390/ijms14034885

132. Giannakoula AE, Ilias IF. The effect of water stress and salinity on growth and physiology of tomato *(Lycopersicon esculentum* Mill.). Arch Biol Sci (Belgrade). 2013;65(2):611-20. https://doi.org/10.2298/ABS1302611G

133. Hamooh BT, Sattar FA, Wellman G, Mousa MAA. Metabolomic and biochemical analysis of two potato (*Solanum tuberosum* L.) cultivars exposed to in vitro osmotic and salt stresses. Plants (Basel). 2021;10(1):98. https://doi.org/10.3390/plants10010098

134. Genzel F, Dicke MD, Junker-Frohn LV, Neuwohner A, Thiele B, Putz A, et al. Impact of moderate cold and salt stress on the accumulation of antioxidant flavonoids in the leaves of two Capsicum cultivars. J Agric Food Chem. 2021;69(23):6431-43. https://doi.org/10.1021/acs.jafc.1c00908

135. Fidalgo F, Santos I, Teixeira J, Araújo SS, Salema R. Effects of long-term salt stress on antioxidant defence systems, leaf water relations and chloroplast ultrastructure of potato plants. Ann Appl Biol. 2004;145(2):185–92. https://doi.org/10.1111/j.1744-7348.2004.tb00374.x

136. Hossain MM, Nonami H. Effect of salt stress on physiological response of tomato fruit grown in hydroponic culture system. Hort Sci (Prague). 2012;39(1):26-32. https://doi.org/10.17221/63/2011-HORTSCI

137. Huez-López MA, Ulery AL, Samani Z, Picchioni G, Flynn RP. Response of chile pepper (*Capsicum annuum* L.) to salt stress and organic and inorganic nitrogen sources: I. Growth and yield. Trop Subtrop Agroecosyst. 2011;14(1):137–47. https://doi.org/10.56369/tsaes.681

138. Abul-Soud MA, Abd-Elrahman SH. Foliar selenium application to improve the tolerance of eggplant grown under salt stress conditions. Int J Plant Soil Sci. 2015;9(1):1–10. https://doi.org/10.9734/IJPSS/2016/19992

139. Naeem M, Basit A, Ahmad I, Mohamed HI, Wasila H. Effect of salicylic acid and salinity stress on the performance of tomato plants. Gesunde Pflanzen. 2020;72(4):393–402. https://doi.org/10.1007/s10343-020-00521-7

140. Königshofer H, Tromballa HW, Löppert HG. Early events in signalling high-temperature stress in tobacco BY-2 cells involve alterations in membrane fluidity and enhanced hydrogen peroxide production. Plant Cell Environ. 2008;31(12):1771–80. https://doi.org/10.1111/j.1365-3040.2008.01880.x

141. Abbas Y, Mansha S, Waheed H, Siddiq Z, Hayyat MU, Zhang YJ, et al. NaCl stress, tissue-specific Na^+ and K^+ uptake and their effect on growth and physiology of *Helianthus annuus* L. and *Solanum lycopersicum* L. Sci Hortic. 2024;326:112454. https://doi.org/10.1016/j.scienta.2023.112454

142. Ji L, Li P, Su Z, Li M, Guo S. Cold-tolerant introgression line construction and low-temperature stress response analysis for bell pepper. Plant Signal Behav. 2020;15(7):1773097. https://doi.org/10.1080/15592324.2020.1773097

143. Camejo D, Rodríguez P, Morales MA, Dell'Amico JM, Torrecillas A, Alarcón JJ. High temperature effects on photosynthetic activity of two tomato cultivars with different heat susceptibility. J Plant Physiol. 2005;162(3):281–9. https://doi.org/10.1016/j.jplph.2004.07.014

144. Hazra P, Samsul HA, Sikder D, Peter KV. Breeding tomato (*Lycopersicon esculentum* Mill.) resistant to high temperature stress. Int J Plant Breed. 2007;1(1):31–40.

145. Rivero RM, Ruiz JM, Romero L. Oxidative metabolism in tomato plants subjected to heat stress. J Hortic Sci Biotechnol. 2004;79 (4):560–64. https://doi.org/10.1080/14620316.2004.11511805

146. Bai C, Wu C, Ma L, Fu A, Zheng Y, Han J, et al. Transcriptomics and metabolomics analyses provide insights into postharvest ripening and senescence of tomato fruit under low temperature. Hort Plant J. 2023;9(1):109-21. https://doi.org/10.1016/j.hpj.2021.09.001

147. Luthra SK, Gupta VK, Lal M, Tiwari JK. Genetic parameters for tuber yield components, late blight resistance and keeping quality in potatoes (*Solanum tuberosum* L.). Potato J. 2018;45(2):107-115.

148. Rykaczewska K. The impact of high temperature during growing season on potato cultivars with different response to environmental stresses. Am J Plant Sci. 2013;4(12):2386–93. http://doi.org/10.4236/ajps.2013.412295

149. Tiwari RK, Lal MK, Naga KC, Kumar R, Chourasia KN, Subhash S, et al. Emerging roles of melatonin in mitigating abiotic and biotic stresses of horticultural crops. Sci Hortic. 2020;272:109592. https://doi.org/10.1016/j.scienta.2020.109592

150. Morris WL, Hancock RD, Ducreux LJM, Morris JA, Usman M, Verrall SR, et al. Day-length dependent restructuring of the leaf transcriptome and metabolome in potato genotypes with contrasting tuberization phenotypes. Plant Cell Environ. 2014;37 (6):1351–63. https://doi.org/10.1111/pce.12238

151. Saha SR, Hossain MM, Rahman MM, Kuo CG, Abdullah S. Effect of high temperature stress on the performance of twelve sweet pepper genotypes. Bangladesh J Agric Res. 2010;35(3):525–34. ttps://doi.org/10.3329/bjar.v35i3.6459

152. Airaki M, Leterrier M, Mateos RM, Valderrama R, Chaki M, Barroso JB, et al. Metabolism of reactive oxygen species and reactive nitrogen species in pepper (*Capsicum annuum* L.) plants under low temperature stress. Plant Cell Environ. 2012;35(2):281–295. https://doi.org/10.1111/j.1365-3040.2011.02310.x

153. Zhang J, Jiang X, Li T, Yang Z. Effect of moderately high temperature stress on photosynthesis and carbohydrate metabolism in tomato (*Lycopersicon esculentum* L.) leaves. Afr J Agric Res. 2012;7(3):487–492. https://doi.org/10.5897/AJAR11.2062

154. Zhang Z, Lan M, Han X, Wu J, Wang-Pruski G. Response of ornamental pepper to high-temperature stress and role of exogenous salicylic acid in mitigating high temperature. J Plant Growth Regul. 2020;39:133–146. https://doi.org/10.1007/s00344-019-09969-y

155. Li Y, Ren K, Hu M, He X, Gu K, Hu B, et al. Cold stress in the harvest period: effects on tobacco leaf quality and curing characteristics. BMC Plant Biol. 2021;21(1):131. https://doi.org/10.1186/s12870-021-02895-w

156. Jin J, Zhang H, Zhang J, Liu P, Chen X, Li Z, Xu Y, Lu P, Cao P. Integrated transcriptomics and metabolomics analysis to characterize cold stress responses in *Nicotiana tabacum*. BMC Genomics. 2017;18(1):496. https://doi.org/10.1186/s12864-017-3871-7

157. Concellón A, Anon MC, Chaves AR. Effect of low temperature storage on physical and physiological characteristics of eggplant fruit (*Solanum melongena* L.). LWT Food Sci Technol. 2007;40(3):389–396. https://doi.org/10.1016/j.lwt.2006.02.004

158. Rajitha KD, Channakeshava BC, Bhanuprakash K. Differential response of brinjal (*Solanum melongena* L.) genotypes for high temperature stress on seed quality traits and peroxidase activity. Int J Curr Microbiol Appl Sci. 2018;7(5):3131–3141. https://doi.org/10.20546/ijcmas.2018.705.366

159. Nothmann J, Koller D. Effects of low-temperature stress on fertility and fruiting of eggplant (*Solanum melongena*). Exp Agric. 1975;11 (1):33–38. https://doi.org/10.1017/S0014479700006207

160. Wu X, Yao X, Chen J, Zhu Z, Zhang H, Zha D. Brassinosteroids protect photosynthesis and antioxidant system of eggplant seedlings from high-temperature stress. Acta Physiol Plant. 2014;36:251–261. https://doi.org/10.1007/s11738-013-1406-7

161. Piacentini D, Della Rovere F, Lanni F, Cittadini M, Palombi M, Fattorini L, et al. Brassinosteroids interact with nitric oxide in the response of rice root systems to arsenic stress. Environ Exp Bot. 2023;209:105287. https://doi.org/10.1016/j.envexpbot.2023.105287

162. Puzanskiy RK, Yemelyanov VV, Shavarda AL, Gavrilenko TA, Shishova MF. Age- and organ-specific difference of potato (*Solanum phureja*) plant metabolome. Russ J Plant Physiol. 2018;65:813–823. https://doi.org/10.1134/S1021443718060122

163. Rabara RC, Tripathi P, Reese RN, Rushton DL, Alexander D, Timko MP, et al. Tobacco drought stress responses reveal new targets for

Solanaceae crop improvement. BMC Genomics. 2015;16:484. https://doi.org/10.1186/s12864-015-1575-4

164. Aydın Akbudak M, Yildiz S, Filiz E. Pathogenesis-related protein-1 (PR-1) genes in tomato (*Solanum lycopersicum* L.): bioinformatics analyses and expression profiles in response to drought stress. Genomics. 2020;112(6):4089–4099. https://doi.org/10.1016/j.ygeno.2020.07.004

165. Naik B, Kumar V, Rizwanuddin S, Chauhan M, Choudhary M, Gupta AK, et al. Genomics, proteomics and metabolomics approaches to improve abiotic stress tolerance in tomato plant. Int J Mol Sci. 2023;24(3):3025. https://doi.org/10.3390/ijms24033025

166. Senthilkumar KM, Raju S, Velumani R, Gutam S. Transcriptome analysis and identification of leaf, tuberous root and fibrous root tissue-specific high temperature stress-responsive genes in sweet potato. J Hortic Sci. 2023;18(1):53-59. https://doi.org/10.24154/jhs.v18i1.2131

167. Abbas A, Mansha S, Waheed H, Siddiq Z, Hayyat MU, Zhang Y, et al. NaCl stress, tissue-specific Na^+ and K^+ uptake and their effect on growth and physiology of *Helianthus annuus* L. and *Solanum lycopersicum* L. Sci Hortic. 2024;326:112454. https://doi.org/10.1016/j.scienta.2023.112454

168. Pang X, Chen J, Li L, Huang W, Liu J. Deciphering drought resilience in Solanaceae crops: unraveling molecular and genetic mechanisms. Biology (Basel). 2024;13(12):1076. https://doi.org/10.3390/biology13121076

169. Villarino GH, Hu Q, Scanlon MJ, Mueller L, Bombarely A, Mattson NS. Dissecting tissue-specific transcriptomic responses from leaf and roots under salt stress in Petunia hybrida Mitchell. Genes (Basel). 2017;8(8):195. https://doi.org/10.3390/genes8080195

170. Akbudak AM, Yildiz S, Filiz E. Pathogenesis-related protein-1 (PR-1) genes in tomato (*Solanum lycopersicum* L.): bioinformatics analyses and expression profiles in response to drought stress. Genomics. 2020;112(6):4089–4099. https://doi.org/10.1016/j.ygeno.2020.07.004

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